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ORIGINAL PAPER

Soil chemical quality indicators for agricultural life cycle assessment: a case of study in Brazil

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Abstract
Modern agriculture has had to face complex environmental issues, many of which result from land use, which includes the degradation of its fertility properties. Soil quality is fundamental to the sustainability of the planet, as it also affects other natural resources. Therefore, it must be seen as a fundamental action for the sustainability of the planet and be evaluated using methodologies capable of holistically relating the environmental impacts of production systems, as does the Life cycle assessment (LCA) methodology. However, due to the lack of suitable models, LCA is still ineffective in assessing soil quality. Therefore, our objective was to evaluate the use of chemical soil quality indicators in the context of LCA, contributing new information to the debate. To this end, a set of soil quality indicators from the APOIA-NovoRural method were applied in some agricultural production systems in southern Brazil. Thus, the LCA results confirmed soil quality maintenance activities as those that most contribute to impacts, particularly in the categories of climate change, (eco)toxicities and land use. However, the indicators efficiently contributed direct information about the agricultural environment, relating them to the impacts estimated by the LCA. Therefore, the use of indicators makes it possible to improve soil management by adjusting chemical parameters, accurately contextualizing activities, and use of inputs to the real conditions of the area assessed. Thus, we demonstrate that indicators can be useful in providing information for agricultural environmental management in interrelation with LCA, whose application alone is not yet capable of achieving such results.

Keywords Agricultural LCA · Sustainable agriculture · Soil management · Soil indicators · Environmental assessment

Introduction

Although agriculture is recognized for its importance for the maintenance and well-being of humanity and the global economy, the modern agriculture, which has reached

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industrial dimensions, still tries to prove that it is capable of being sustainable (Dong 2021; Saikanth et al. 2023). This premise is imposed by the fact that agriculture is an activity directly connected to the common pool of natural resources and that for it to be practiced it depends on the conversion of natural areas, which implies the native vegetation loss to production areas (Gaffney et al. 2019; Pendrill et al. 2022). Due to its characteristics, agriculture must deal with relatively complex environmental issues, such as: water consumption and quality; greenhouse gas emissions; deforestation and loss of biodiversity; excessive consumption of inputs; and degradation of soil quality.

Agronomically, soil quality is defined as the ability of a soil to support the productivity of plants and animals, while maintaining water and air quality (Bongiorno et al. 2019; Doran 2002). Therefore, through its chemical, physical, and biological parameters, the soil is responsible for maintaining biomass and nutrient, carbon and water cycles. This means that its poor management results in unwanted carbon emissions, water contamination and the maintenance of essential ecosystem services, with soil therefore being a key factor in many of the environmental issues related to agriculture (Schreefel et al. 2020). Furthermore, as natural resources are globally interconnected, it is essential that the search for evaluating and mitigating such types of impacts arising from complex issues, such as agriculture, are carried out using holistic approach methods capable of considering the impacts for the different emission compartments (air, water, and soil) in the same study. The assessment scale (local and global) is another important factor to be considered in agricultural environmental assessment (Bai et al. 2018; Doran 2002), because although many agricultural production chains are global, productions in the field will always have to deal with local edaphoclimatic characteristics.

The Life cycle assessment (LCA) methodology is considered one of the best for quantifying and evaluating the environmental impacts of complex production systems at different assessment scales (Hellweg and Millà i Canals 2014). The methodology was developed by the industrial sector in the 1970s with the aim of quantifying the proportion of input imports per final product. It was only in the 1990s that its application to agricultural systems began (Bauman and Tillman 2004). However, even though LCA has since been increasingly used by the agricultural sector, it still presents several gaps in its assessments for the sector (van der Werf et al. 2020). One of these gaps, and currently one of its main challenges for its methodological development, is the difficulty in creating or even finding methods or tools capable of integrating the methodology and allowing its assessments to include soil quality (Garrigues et al. 2012; van der Werf et al. 2020; Vidal Legaz et al. 2017).

Although there have been efforts by the LCA community to improve its evaluations of impacts related to soil, its properties and functions are still incorporated to a limited extent in the methodology. The main issues that affected the development of these assessments are: (i) the lack of a clear and consistent chain of cause and effect; (ii) to find an impact trajectory that systematically describes causal relationships from inventory data to intermediate and final indicators; (iii) current models applicable to LCA are unable to comprehensively describe the multiple impacts derived from land use and changes in land use, in addition to many of the models are not originally based on site-specific studies and require additional effort to adapt to other locations and dimensions; (iv) models used to assess potential impacts often differ from each other, making results incomparable (Allacker et al. 2014; Vidal Legaz et al. 2017).

Furthermore, the main current suggestions for addressing impacts on soil quality in LCA studies have prioritized mainly physical parameters and rarely chemical and biological ones (Alvarenga et al. 2015; Brandão and Milà i Canals 2013; Bos et al. 2016; Garrigues et al. 2013; Oberholzer et al. 2012; Saad et al. 2013). Due to the current lack of tools capable of being converted to appropriate methods and inserted into the methodology and the difficulty in developing them in the short term, one of the alternatives has been to evaluate soil quality separately from LCA, avoiding completely neglecting the impacts on quality soil and seeking information that can contribute to the debate on this topic (Vidal Legaz et al. 2017).

Therefore, our objective in this study was to evaluate the use of a conventional environmental impact assessment method (APOIA-NovoRural) and provide relevant information that contributes to the debate on how to assess soil quality in LCA studies and develop a baseline knowledge about the applicability of soil chemical quality indicators in conjunction with LCA in agricultural production systems.

Materials and methods

Proposal concept

Based on the need to improve the level of information on the assessment of soil quality in LCA studies, the soil chemical quality indicators present in the Environmental Impact Assessment (EIA) method APOIA-NovoRural (Rodrigues et al. 2003, 2006) were applied and evaluated in this study. The main information about the methods and their application is presented in the following topic.

Life cycle assessment (LCA)

The LCA methodology was applied in accordance with ISO 14040 (2006) and ISO 14044 (2006) standards, undertaking its four phases: (i) definition of the objective and scope; (ii) inventory analysis; (iii) impact assessment; (iv) interpretation. However, because the standards do not define a single way of conducting an LCA study, and complementary methods and indicators can be implemented according to the needs of each type of study. Therefore, here for the first time it was applied the indicators of the APOIA-NovoRural method (Rodrigues et al. 2003, 2006) together with the LCA.

APOIA-NovoRural

APOIA-NovoRural [Sistema de Avaliação Ponderada de Impacto Ambientais de Atividades do NovoRural (pt)—Weighted environmental impact assessment system for NovoRural activities (en)] is an EIA method for rural activities proposed to assist in technological adaptation and management of agricultural territorial activities on a local scale (on the farm) (Rodrigues et al. 2003, 2006), thus, it allows the development of activities and production chains in the agricultural sector (Buchinelli et al. 2007; Rodrigues et al. 2007).

The APOIA-NovoRural method was developed in accordance with the main premises of EIA science: (i) evaluate various rural activities, in different regions and environmental situations, at a local scale; (ii) include management indicators involved in sustainable local development; (iii) facilitate the detection of critical points for management correction; (iv) express the results in a simple and direct way to farmers and rural entrepreneurs, decision-makers and the general public; (v) provide an integrated final measure of the environmental impact and sustainability of the assessed rural activities, contributing to environmental management and ecocertification, in order to respond to the demand of producers and organizations (Rodrigues 2009; Rodrigues et al. 2010).

The method consists of sets of indicators built on scalar weighting matrices, designed to systematize the activities evaluated. In an analytical-quantitative way, the method evaluates the effects of activities on each of its indicators. The method consists of 62 indicators, for five dimensions of sustainability: landscape ecology; environmental quality (atmosphere, water, and soil); sociocultural values; economic values; and management and administration (Rodrigues 2009). Due to the objective of this study, we adopted only the solo module.

The weighting factors are responsible for determining the impact indexes. They were constructed through a review of impact assessment methods, debates between experts and validated through evaluations. The complete set of indicators is available in Rodrigues et al. (2003). The weighting matrices were constructed to transform the indicator variables into impact indexes, according to utility functions (normalized scale from 0 to 1, with a base value of environmental compliance standardized at 0.7) and baselines expressed for each indicator. They were derived from probability and sensitivity tests (Rodrigues et al. 2003; Girardin et al. 1999). A probability test was applied to define the minimum and maximum limits of the scales, in addition to their conformity value (0.7), according to the numerical solution of the variable that defines the indicator. A sensitivity test was also applied to direct the indicator's results into positive or negative, through the meaning of the changes caused in the activity evaluated according to a quantitative association with the performance established in the baseline. The tests allow the creation of correspondence tables between the indicator's impact indexes and the utility values, with the impact index subsequently expressed graphically. They were then combined by averaging the utility values of each dimension considered and the set of indicators, composing a sustainability diagram for the dimension evaluated and for the entire area (Rodrigues 2009).

The difference between quality index (environmental performance) and impact (percentage change) is: Quality—corresponds to the utility value and the current state of the soil, referring to its expected sustainability; Impact—corresponds to the variation in the effect of the situation assessed on site, changing between the two periods, before and after (unchanged = 0.7). According to Rodrigues (2009) weighting factors have also been used to measure the levels of cause and damage of observed impacts and percentage variation scales of impacts. Details about the construction of the system and the weighting matrices are present in Rodrigues et al. (2003). We decided to apply the indicators of the APOIA-NovoRural method in this study, in addition to having their quality proven by several studies, they follow the principles of creating models recommended by the OECD (OECD 1999): (i) analytical soundness: based on solid science; (ii) easy to interpret: essential information communicated to users; (iii) measurable: data that can be collected and measured realistically, considering spatial and temporal considerations. Furthermore, APOIA-NovoRural

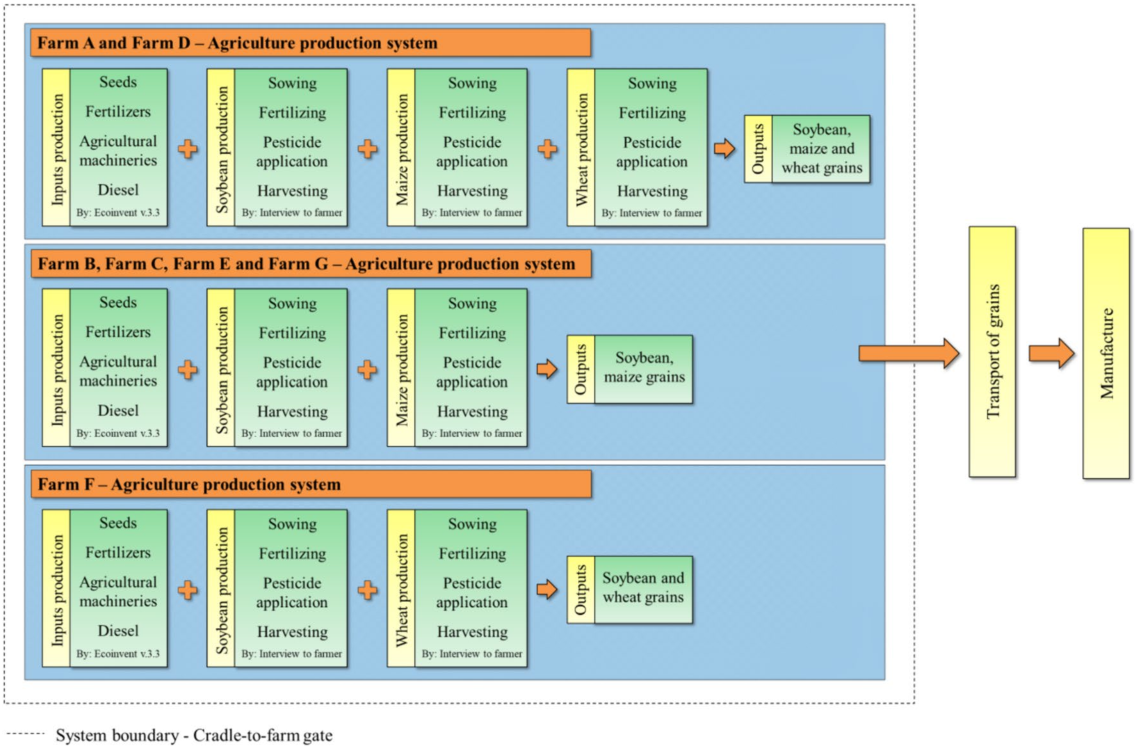


Fig. 1 Flowchart of the boundaries of the production systems (cradle-to-farm gate) evaluated in this study

was recommended by de Olde et al. (2018) as a method with a strong implementation character and contribution to the management of agricultural production systems.

The selected indicators belong to the soil module of the APOIA-NovoRural method. The indicators applied were: (1) soil organic matter (SOM); (2) pH; (3) phosphorus (P); (4) exchangeable potassium (K); (5) exchangeable calcium/magnesium (Ca/Mg); (6) potential acidity (H + Al); (7) sum of bases; (8) cation exchange capacity (CEC); (9) base saturation. The complete set of indicators and more detailed information are available in Rodrigues (2009), in addition, we provide an interactive table for practical use of the indicators in Supplementary Material I.

Combining LCA and APOIA-NovoRural

An environmental assessment of a production system using a single methodology may not guarantee that the best alternatives for its improvement will be found. It is plausible to consider that improvement can be achieved by factors that are not being evaluated or that coexist in the system and are not perceived by the methodology. Collaboration between different methodologies makes it possible to achieve a better understanding of the evaluated system and generate more complex strategies to improve it (Nawrocka and Parker 2009). Thus, the combination of soil chemical quality indicators and LCA should expand the parameters evaluated, going beyond the limits of both methods. The use of new indicators in conjunction with LCA is properly seen as a starting point to expand its evaluation limits.

Therefore, in this study, the relationship between APOIA-NovoRural and LCA occurs through the association of their results. The LCA defines the impacts arising from inputs (substances and activities) and consumption of natural resources in their respective impact categories and the indicators indicate the effects on the environment (soil) of the production system. The connection between its results should support the environmental management of production systems.

Table 1 Scope of the production systems of seven farms presents in Rolândia county, Paraná state—Brazil

	Farms						
	A	B	C	D	E	F	G
Product system	Production processes for grains, inputs and diesel oil						
Function	Produce soybeans, maize and wheat	Produce soybeans and maize	Produce soybeans and maize	Produce soybeans, maize and wheat	Produce soybeans and maize	Produce soybeans and wheat	Produce soybeans and maize
Crops/ Agricultural year							
2015	Soybean/Maize	Soybean/Maize	Soybean/Maize	Soybean/Wheat	Soybean/Maize	Soybean/Wheat	Soybean/Maize
2017	Soybean/Wheat	Soybean/Maize	Soybean/Maize	Soybean/Maize	Soybean/Maize	Soybean/Wheat	Soybean/Maize
Functional unit	1 kg of grains for two years of the production systems						
Reference unit (1 ha^{-1})	4500 kg of soybean, 6180 kg of maize and 3120 kg of wheat	4500 kg of soybean and 7200 kg of maize	4500 kg of soybean and 7200 kg of maize	4500 kg of soybean, 6400 kg of maize and 3230 kg of wheat	4500 kg of soybean and 6000 kg of maize	4500 kg de soybean and 2640 kg of wheat	3960 kg de soybean and 6400 kg of maize
Data source	Information on agricultural inputs and practices (inventories) are present in item 2.6.2. The inventories on the production of inputs and diesel came from the Ecoinvent v. 3.3						
Product system frontier	A cradle-to-farm gate approach was adopted to produce grains, agricultural inputs and diesel						

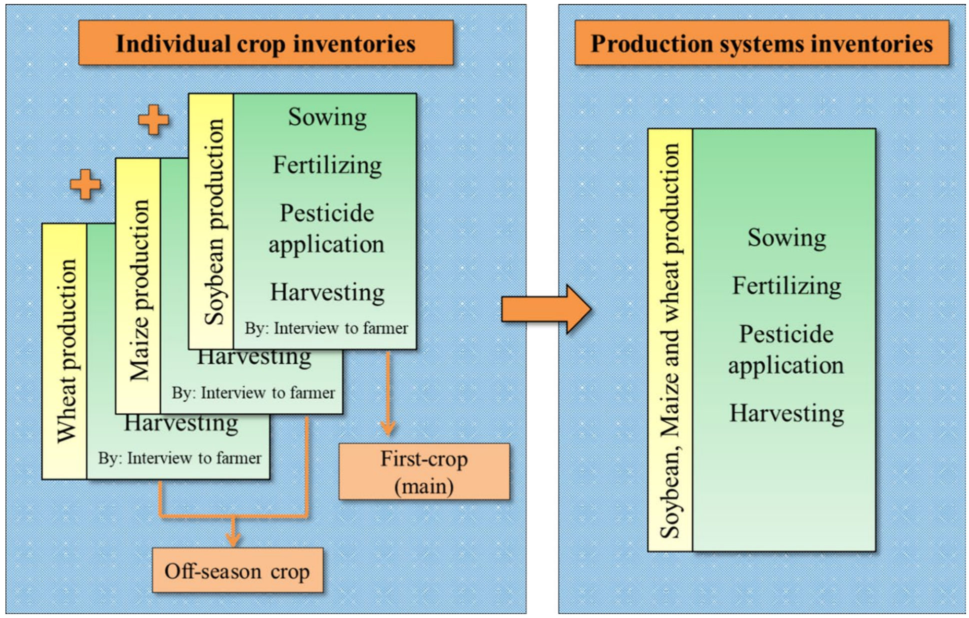


Fig. 2 Process of obtaining inventories of production systems

Case study

Agricultural production and data source

In this study, it was evaluated seven farms (production systems) in southern Brazil—located in the municipality of Rolândia, state of Paraná. This region was selected because it is an important agricultural region where the production systems evaluated have been practiced for a long time and are already consolidated. Data collection was carried out in 2015 and 2017. Five of the production systems are composed of two crops (soybeans and maize—four farms; soybeans and wheat—one farm) and three of them are made up of three crops (soybeans, maize, and wheat). Soybeans are considered the main crop (grown in summer) and maize or wheat are off-season crops (grown in winter). In Fig. 1, it is present the production systems of each farm.

The inputs used differed according to the farm and are specified in 2.2.3.2 Life cycle inventory (LCI). Considering that this study is a test with the purpose of evaluating the use of indicators in a new context, we opted for a reality with little variation in context.

Soil sampling and analysis

The indicators of APOIA-NovoRural method require information that is achieved through soil sampling and laboratory analysis. In this way, we sampled the soil through transects that considered the unevenness of the areas (farms), thus, the number of points sampled for each farm varied according to the topography and the need for points for better sampling. The total was 46 samples per year, divided between the farms as follows: Farm A—6 points; Farm B—6 points; Farm C—9 points; Farm D—5 points; Farm E—12 points; Farm F—3 points; G Farm—5 points. The depth of the samples was 0–20 cm.

The analyzes of soil chemical parameters analyzed were: (i) soil organic matter (SOM); (ii) pH; (iii) phosphate (P)—phosphorus; (iv) exchangeable potassium (K); (v) exchangeable calcium (Ca) and magnesium (Mg); (vi) potential acidity (H + Al); (vii) sum of bases; (viii) cation exchange capacity (CEC); (ix) base saturation. The analysis methods were: P, K = Mehlich extractor 1; Ca, Mg, Al = 1 M KCl extractor; H + Al = estimation by pH SMP, using calibration curves appropriate to the soil used; organic carbon = oxidation by potassium dichromate and quantification by the colorimetric method; pH = 0.01 M. $CaCl_2$.

The values applied to the indicators were the average values of the total points sampled on each farm. The result of

Table 2 Inputs of the production systems of seven farms presents in Rolândia county, Paraná state—Brazil

	Farms						
	A	B	C	D	E	F	G
	kg/ha^{-1}						
Seeding							
Seeds	278	140	188	290	156	408	150
Fertilizers							
Lime	2070	–	–	2070	–	900	830
Plaster	2070	–	–	–	–	–	–
Urea	150	342	23.4	31.7	29.3	77.4	66.9
P_2O_5	46.2	44.6	20.7	37	18.7	40.2	99.9
K_2O	90.8	1.36	6.44	113	75.2	130	138
Herbicides							
2,4-D	1.9	1.34	1.69	1.94	1.34	2.42	2.68
Alkylbenzene	–	–	1.07	–	–	–	1.07
Atrazine	–	1.24	–	–	–	–	4,15
Cletodim	–	–	0.98	–	–	–	0.398
Diclosulam	–	–	–	–	–	–	0.556
Diuron	–	–	–	–	0.414	–	–
Glyphosate	1.5	5.04	10.9	7.95	5.96	8.28	7.88
Haloxifop-p-methyl	–	–	–	–	–	–	0.224
Mesotrione	–	–	–	–	0.163	–	–
Methyl sulfurom	0.0024	–	–	0.0048	–	0.0048	–
Nicosulfuron	–	–	–	–	0.0232	–	–
Paraquat	–	–	0.84	–	0.828	–	1.66
Total	3.4	7.62	14.9	9.9	8.73	10.7	18.6
Inseticides							
Abmectin	–	–	0.414	–	–	–	–
Acephate	–	–	0.315	1.25	–	–	–
Beta-Cyfluthrin	–	–	–	–	–	–	–
Bifenthrin	–	0.029	–	–	–	–	0.075
Clothianidin	–	–	0.084	–	–	–	–
Chlorantraniliprole	–	–	0.021	–	–	–	–
Fipronil	0.156	0.15	–	0.05	0.15	–	0.1
Imidacloprid	–	0.355	–	–	–	0.225	0.73
Lambda-*Cyhalothrin*	0.078	0.0424	0.188	0.162	0.148	0.053	–
Lefenurom	–	–	–	0.0075	–	0.015	–
Methomyl	–	–	–	–	–	–	0.432
Teflubenzuron	–	0.186	0.186	–	–	–	0.249
Thiamethoxam	0.099	0.0564	0.247	0.3	0.162	0.0705	–
Thiodicarb	–	0.0000269	–	–	–	0,315	0,315
Total	0.333	0.819	1.45	1.76	0.461	0.679	1.9
Fungicides							
Azoxystrobin	–	0.252	2.09	0.126	0.232	0.252	0.451
Benzovindiflupir	–	0.126	0.126	0.063	–	0.126	0.09
Carbendazim	–	–	–	–	–	–	–
Ciproconazole	–	–	0.672	–	0.928	–	0.464
Difeconazole	–	–	0.21	0.105	–	–	–
Epoxiconazole	0.157	0.05	–	0.057	–	–	0.113
Fludioxonil	–	–	–	0.00375	–	0.01	–
Flutriafol	–	–	0.155	–	–	–	0.155
Fluxapiroxade	–	–	–	0,0701	–	–	–

Table 2 (continued)

	Farms						
	A	B	C	D	E	F	G
	kg/ha^{-1}						
Mancozeb	2.25	–	–	–	–	–	–
Metalaxyl-M	–	–	–	0.0015	–	0.004	–
Pyraclostrobin	0.421	0.148	–	14.1	0.015	–	0.228
Propiconazole	–	–	0.21	0.105	–	–	–
Protioconazole	–	–	–	–	–	0.144	0.14
Tebuconazole	–	–	–	0.248	–	0.372	–
Methyl thiophanate	0.045	0.135	–	0.045	0.135	–	0.09
Trifloxystrobin	–	–	–	0.124	–	0.26	0.012
Total	2.87	0.711	3.46	15.1	1.31	0.927	1.74
Other							
Mineral oil	0.96	1.03	7.84	0.96	0.96	–	3.36

the analysis and the averages adopted are presented in Supplementary Material II, Table 1.

Life cycle assessment (LCA)

Scope The study scope is presented in Table 1.

Life cycle inventory (LCI) The LCI were developed through interviews with farmers, to whom a questionnaire was administered to identify inputs and their quantities, as well as agricultural operations. For all production systems, soybeans were adopted as the main crop in the two years evaluated, while in the off-season there was variation between maize and wheat. The LCI of production systems were prepared considering all crops from the same inventory during an agricultural period of two years for each farm. To do this, we initially collect information and create individual inventories for each crop, main and off-season, to identify the activities and inputs of each culture within the final inventories that represent the production systems. In Fig. 2, it is present the process of preparing production system inventories, based on individual inventories.

Inventories relating to the production of inputs and agricultural operations come from the Ecoinvent 3.3 database. Table 2 shows the amount of inputs consumed on each farm.

Emissions and life cycle impact assessment (LCIA) Fertilizer emissions were estimated according to Nemecek and Schnetzer (2011), Canals (2003) and IPCC (2006) for: ammonia to the atmosphere; leaching of nitrate into groundwater; phosphorus through erosion in surface waters; N_2O and NO_X for atmosphere; fossil CO_2 from limestone; heavy metals for soil, surface and groundwater; and CO_2 to the atmosphere. CO_2 emissions by land use change, it was estimated according to Novaes et al. (2017).

We disregard phosphorus leaching emissions into groundwater and surface runoff, due to the low mobility of phosphorus in Brazilian soil, in addition to the scarcity of the nutrient in the soil, only 0.1% of the total is in the form of P solution, which can be converted into non-labile forms by the fixation mechanism and, consequently, non-leachable (Novais and Smyth 1999). The emission of phosphorus adsorbed by soil particles lost through erosion was also disregarded due to the lack of models to determine it.

For pesticide emissions we adopted the approach of 100% of emissions reaching the ground (Nemecek and Schnetzer 2011). For impact assessment, the ReCiPe, Midpoint (H) V1.02/World ReCiPe H. method was adopted, disregarding impact categories not relevant to the study.

Results and discussion

We present the results separated by methods in individual topics and describe them in a way that highlights the main results that were verified individually for each farm evaluated. This initiative aims to ensure that individual cases are better verified and condensed into a clear, technical text. Thus, it is possible to expand the conception of the action of each methodology on the areas and production systems, as well as the requirements that can enable the methods to be applied again together in new cases.

Results of life cycle assessment (LCA)

The results of the LCA assessments for the seven farms (production systems) considered in this study are presented in Fig. 3. The categories that had the greatest impacts, per unit (because the different impact categories cannot be compared with each other), were: climate change (kg CO_2 eq.);

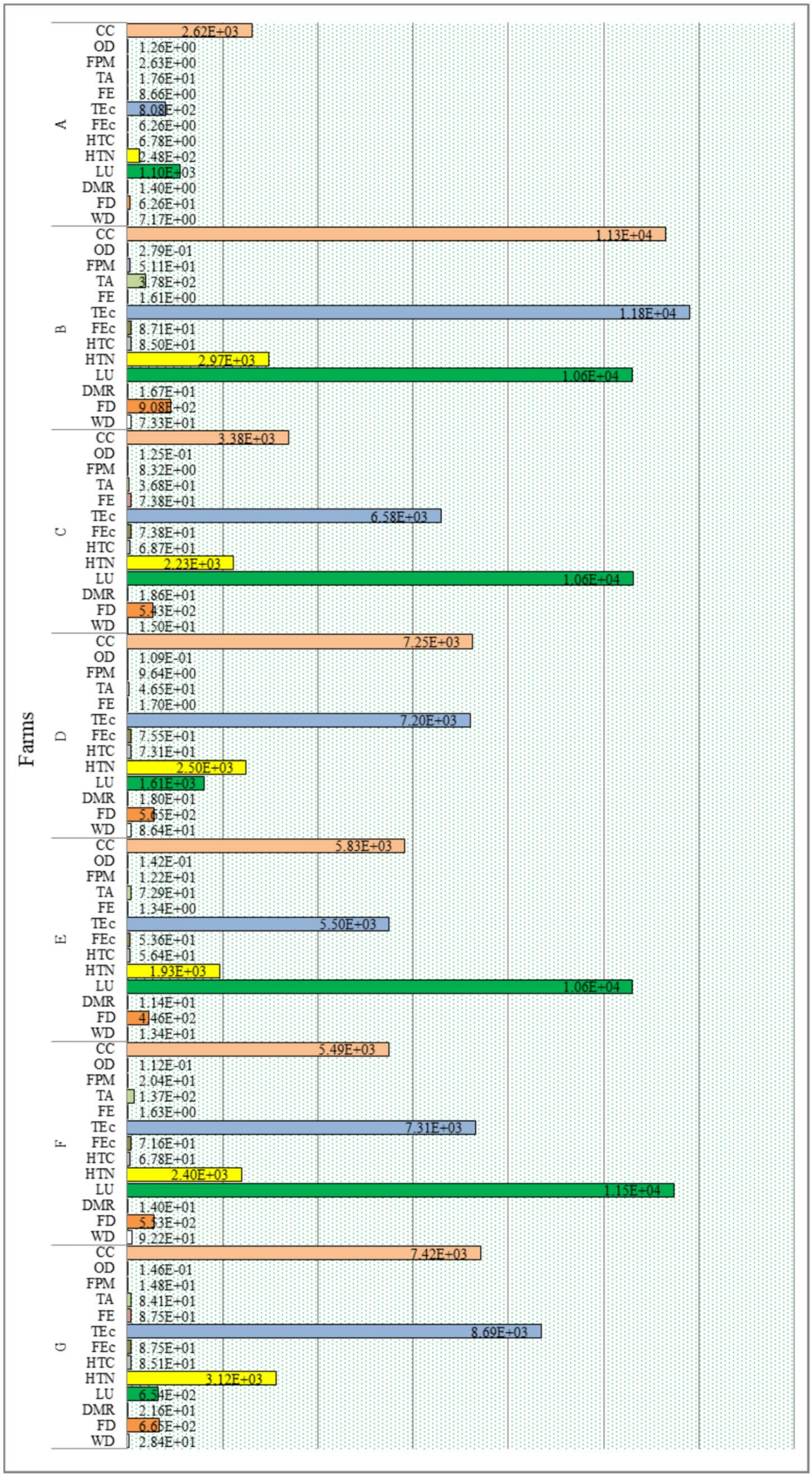


Fig. 3 Environmental performance of seven farms (**A**, **B**, **C**, **D**, **E**, **F**, **G**) presents in Rolândia county, Paraná state, assessed by the Life Cycle Assessment (LCA) methodology for impact categories: Land use (LU)—m^{2}a crop eq.; Terrestrial ecotoxicity (TEc)—kg 1,4-DCB; Climate change (CC)—kg CO_2 eq.; Human toxicity—non-carcinogenic (HTN)—kg 1,4-DCB; Fossil depletion (FD)—kg oil eq.; Terrestrial acidification (TA)—kg SO_2 eq.; Water depletion (WD)—m^3; Freshwater ecotoxicity (FEc)—kg 1,4-DCB; Human toxicity—carcinogenic (HTC)—kg 1,4-DCB; Formation of particulate material (FPM)—kg PM2.5 eq.; Depletion of mineral resources (DMR)—kg Cu eq.; Freshwater eutrophication (FE)—kg P eq.; Ozone depletion (OD)—kg CFC11 eq. See Table 1 to identify the production system of each farm and their respective scopes and Table 2 for the list of inputs

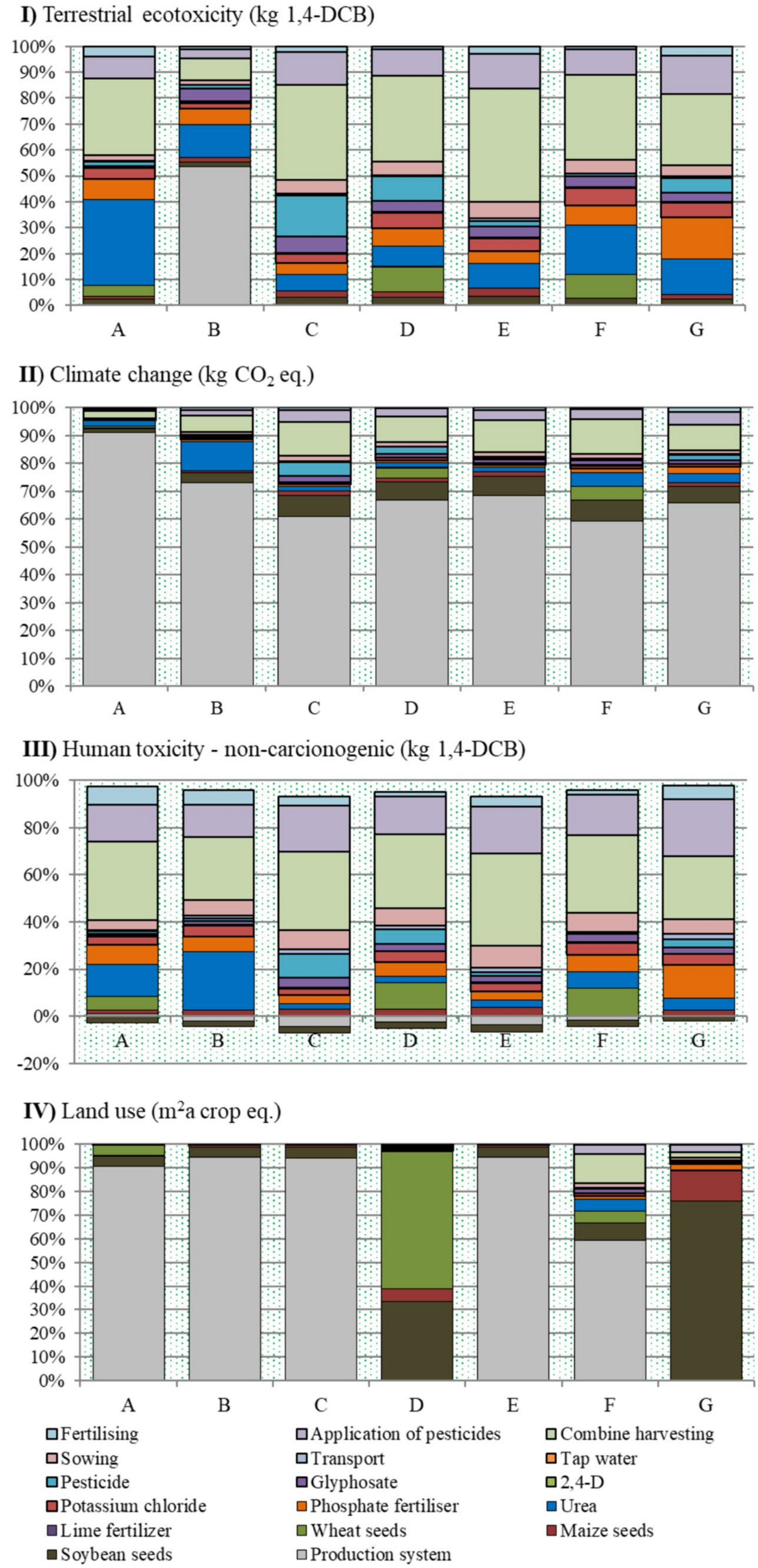
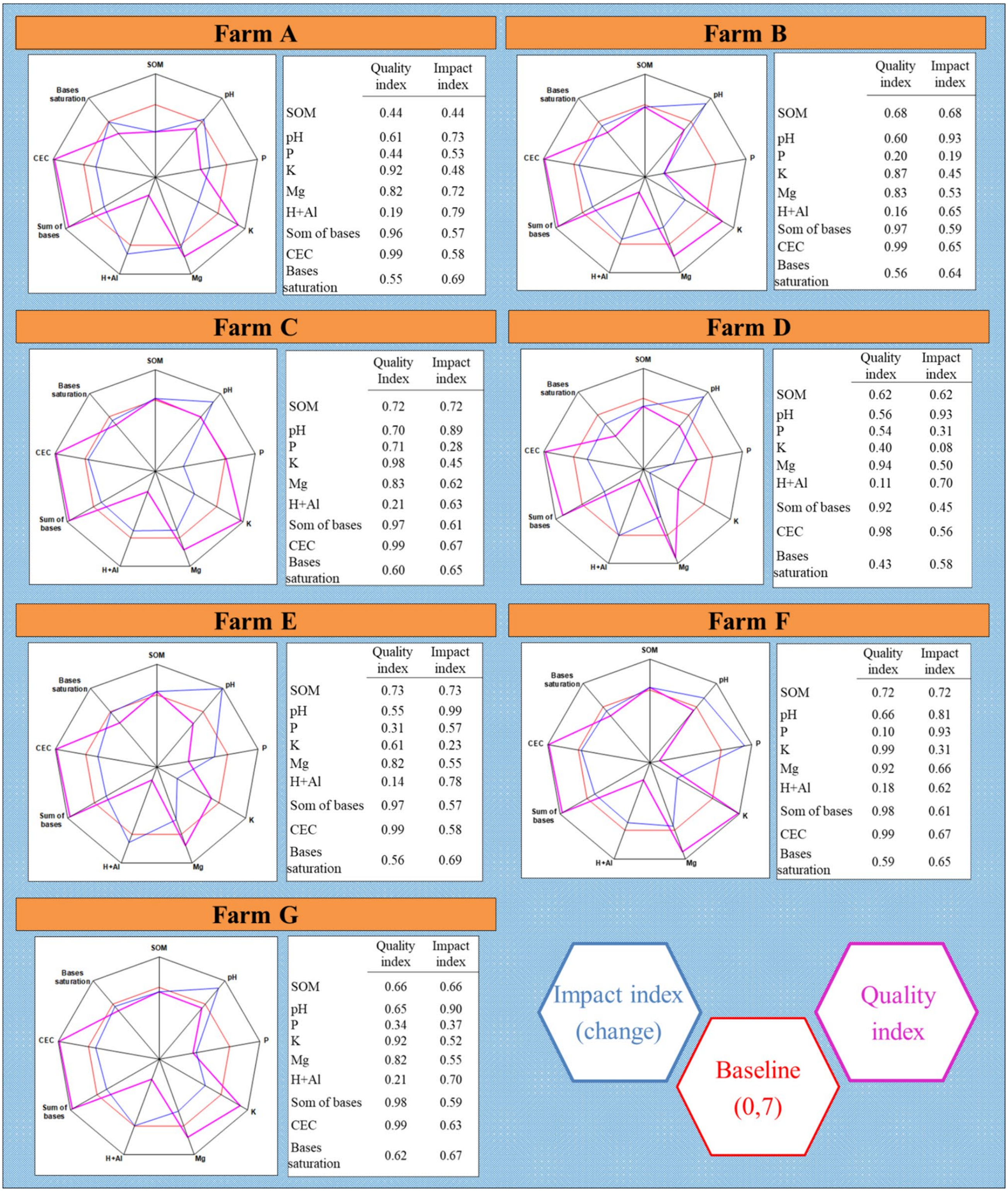


Fig. 4 Contribution of the activities of the production systems of seven farms (**A**, **B**, **C**, **D**, **E**, **F**, **G**) presents in Rolândia county, Paraná state to the performance of the impact categories that most impacted: (I) terrestrial ecotoxicity (TEc) (kg 1,4-DCB); (II) climate change (CC) (kg CO_2 eq.); (III) human toxicity, non-carcinogenic (HTN) (kg 1,4-DCB); IV) land use (LU) (m^2a crop eq.)



Farm A

	Quality index	Impact index
SOM	0.44	0.44
pH	0.61	0.73
P	0.44	0.53
K	0.92	0.48
Mg	0.82	0.72
H+Al	0.19	0.79
Som of bases	0.96	0.57
CEC	0.99	0.58
Bases saturation	0.55	0.69

Farm B

	Quality index	Impact index
SOM	0.68	0.68
pH	0.60	0.93
P	0.20	0.19
K	0.87	0.45
Mg	0.83	0.53
H+Al	0.16	0.65
Som of bases	0.97	0.59
CEC	0.99	0.65
Bases saturation	0.56	0.64

Farm C

	Quality Index	Impact index
SOM	0.72	0.72
pH	0.70	0.89
P	0.71	0.28
K	0.98	0.45
Mg	0.83	0.62
H+Al	0.21	0.63
Som of bases	0.97	0.61
CEC	0.99	0.67
Bases saturation	0.60	0.65

Farm D

	Quality index	Impact index
SOM	0.62	0.62
pH	0.56	0.93
P	0.54	0.31
K	0.40	0.08
Mg	0.94	0.50
H+Al	0.11	0.70
Som of bases	0.92	0.45
CEC	0.98	0.56
Bases saturation	0.43	0.58

Farm E

	Quality index	Impact index
SOM	0.73	0.73
pH	0.55	0.99
P	0.31	0.57
K	0.61	0.23
Mg	0.82	0.55
H+Al	0.14	0.78
Som of bases	0.97	0.57
CEC	0.99	0.58
Bases saturation	0.56	0.69

Farm F

	Quality index	Impact index
SOM	0.72	0.72
pH	0.66	0.81
P	0.10	0.93
K	0.99	0.31
Mg	0.92	0.66
H+Al	0.18	0.62
Som of bases	0.98	0.61
CEC	0.99	0.67
Bases saturation	0.59	0.65

Farm G

	Quality index	Impact index
SOM	0.66	0.66
pH	0.65	0.90
P	0.34	0.37
K	0.92	0.52
Mg	0.82	0.55
H+Al	0.21	0.70
Som of bases	0.98	0.59
CEC	0.99	0.63
Bases saturation	0.62	0.67

Fig. 5 Soil chemical quality indicators by APOIANovoRural for seven farms (**A**, **B**, **C**, **D**, **E**, **F**, **G**) presents in Rolândia county, Paraná state. The results of indicators are expressed by multi-attribute values (0–1) of the quality indexes (IQ = quality index) and environmental impact (II = impact index), compared to the baseline, defined as 0.7. Where: SOM = soil organic matter; P = phosphate (phosphorus); K = exchangeable potassium; Mg = exchangeable calcium and magnesium; H + Al = potential acidity; (7) sum of bases; (8) CEC = cation exchange capacity

terrestrial ecotoxicity (kg 1,4-DCB); land use (m^2a crop eq.); human toxicity, non-carcinogenic (kg 1,4-DCB).

The sequence of the most impactful categories, per unit, for each farm were, respectively: (A) climate change (kg CO_2 eq.), land use (m^2a crop eq.) and terrestrial ecotoxicity (kg 1,4-DCB); (B) terrestrial ecotoxicity (kg 1,4-DCB), climate change (kg CO_2 eq.) and land use (m^2a crop eq.); (C) land use (m^2a crop eq.), terrestrial ecotoxicity (kg 1,4-DCB) and climate change (kg CO_2 eq.); (D) climate change (kg CO_2 eq.), terrestrial ecotoxicity (kg 1,4-DCB) and human, non-carcinogenic toxicity (kg 1,4-DCB); (E) land use (m^2a crop eq.), climate change (kg CO_2 eq.) and terrestrial ecotoxicity (kg 1,4-DCB); (F) land use (m^2a crop eq.), terrestrial ecotoxicity (kg 1,4-DCB), climate change (kg CO_2 eq.); (G) terrestrial ecotoxicity (kg 1,4-DCB), climate change (kg CO_2 eq.) and human, non-carcinogenic toxicity (kg 1,4-DCB). In the Fig. 4 we present the activities that most contributed to impacts in the main impact categories, by unit.

In Figs. 3 and 4 it is possible to notice that in most of the farms evaluated (A, B, C, E and F) among the impact categories that stood out are: climate change (kg CO_2 eq.); land use (m^2a crop eq.); and territorial ecotoxicity (kg 1,4-DCB). For farms D and G, they were: climate change (kg CO_2 eq.); territorial ecotoxicity (kg 1,4-DCB); and human toxicity—carcinogen (kg 1,4-DCB), respectively. As for activities, those that contributed most to these impact categories were: fertilizer use (mainly urea); machine operations (mainly harvesting); and seed production. The other categories were also influenced by these activities, but in a less expressive way.

In this way, the activity related to the use of fertilizers was also relevant in the categories of fossil depletion (kg oil eq.), terrestrial ecotoxicity (kg 1,4-DCB), human toxicity—carcinogenic (kg 1,4-DCB), formation of particulate material (kg PM2.5 eq.) and freshwater ecotoxicity (kg 1,4-DCB). Urea contributed mainly to water depletion (m^3) and simple superphosphate (SSP) in the mineral resource depletion (kg Cu eq.) categories. Fertilization and harvesting operations contributed to the human toxicity—carcinogenic (kg 1,4-DCB) and mineral resource depletion (kg Cu eq.) categories. In relation to soil management, the use of urea and SSP were the activities that most contributed to the impacts.

Results of soil chemical quality indicators

Firstly, it is worth highlighting that when using the average values of the sampled points (average of the parameters referring to the total of points sampled in each area) the indicators were not completely efficient, due to the calculation of averages and the decimal approximation of order of magnitude, demonstrating small variations in average base saturation values. In evaluations per point (without average values) there was no change in the results, expressing the total efficiency of the indicator. However, we chose to use average values as they are more appropriate for the objective of this study.

In the Fig. 5 are presented the results of the evaluations of the indicators of the APOIA-NovoRural method. It is important to highlight that the results of the indicators are expressed by numerical values through the quality and impact indexes, comparing them with the baseline defined as 0.7 (for more information about the indexes, see topic 2.1.2 APOIA-NovoRural). Thus, we noticed that only three farms presented satisfactory results for SOM: C, E and F. Farms B, D and G were close to the baseline, while A was the only one that was below the baseline. In relation to the nutrient, phosphorus was not satisfactory in practically any of the systems evaluated, both in terms of quality and impact indexes. Highlight goes to farm F, which presented the worst quality index, not due to a lack, but due to the excess of nutrients found in the area. On the other hand, potassium, calcium, and magnesium mostly presented satisfactory quality index and unsatisfactory impact index, this indicates that although most soils have nutrient availability, during the evaluation periods, their availability decreased.

For pH, apart from farm D and E, the quality index did not differ much from the baseline and all systems presented satisfactory impact indexes, however, agronomically, the pH values found are adequate for crop development. For the H + Al parameter, unsatisfactory quality and impact indexes were observed for most production systems, two systems presented indexes above the baseline: A and D. The sum of the bases and CTC for all farms, the results were adequate for the quality indexes and inadequate for the impact indexes. The base saturation indexes were unsatisfactory for all properties.

Discussions

Environmental performance of the production system (farms)

According to the LCA assessment of the farms, those that presented the most impacts were B, C, D and E, due to the quantities of inputs provided by the production systems. The most affected impact categories are: terrestrial ecotoxicity (kg 1,4-DCB); climate changes (kg CO_2 eq.); human toxicity, non-carcinogenic (kg 1,4-DCB); land use (m^2a crop eq.), notably. Our results agree with those of Matsuura et al. (2017), who evaluated the soybean-sunflower production system in the Brazilian Cerrado and observed that among the main impact categories were climate change (kg CO_2 eq.) and human toxicity (kg 1,4-DCB). Regarding the activities that contributed to the impacts of the main impact categories, those related to the operation of machines, seed production and use of fertilizers stand out, as in the studies by Castanheira et al. (2015), Maciel et al. (2016), Matsuura et al. (2017) and Zortea et al. (2018). Nemecek et al. (2015), evaluating four agricultural production systems, which included maize cultivation, also noted that machine operations and the use of fertilizers contributed significantly to the main environmental impacts impacted by agricultural production systems. The authors also point out that for the category of climate change (kg CO_2 eq.) (one of the most relevant in the study) the activity that most contributed to the impacts was the use of nitrogen. In this way, both through our study and the scientific literature, Both through our study and the scientific literature, an important relevance for activities related to maintaining soil fertility for the environmental performance of an agricultural system can be noted through LCA assessments.

Through the soil chemical quality indicators, we noticed that many of the soil parameters presented low quality and, in some cases, certain impacts. The SOM, quality and impact parameters were unsatisfactory in four of the seven properties. These unsatisfactory results indicate that there was a reduction in SOM in certain production systems. From the point of view of environmental management, SOM can be a source of carbon for the atmosphere and its decline indicates a possible increase in carbon emissions to the atmosphere, not captured by the methodologies, and which consequently influences the impacts of climate change (Bradford et al. 2016; Sokol et al. 2018). This is an important question regarding impacts on agriculture and should be better assessed using specific methods. Therefore, for Chen et al. (2019) changes in soil carbon stock in response to global warming could substantially alter future climate trajectories, however, despite numerous studies carried out in recent decades, the effects of soil carbon emissions are still not clear to scientists. long-term effects of global warming.

Regarding the CEC parameter, results with adequate quality indexes and unsatisfactory impacts predominated, unlike those observed for H + Al, which presented unsatisfactory quality indexes and satisfactory impact indices in some areas. In general, CEC had an impact on all areas due to the high presence of H + Al, which were present in soils in high quantities. The influence of H and Al on the quality of CEC in a soil was also noted by Aprile and Lorandi (2012) and Gruba and Mulder (2015). However, systems in areas that had satisfactory quality indexes can improve these parameters by adapting agricultural practices, thus avoiding adding more inputs and increasing their impacts. CEC, which represents the graduation of nutrient release capacity, managed correctly can support the maintenance of fertility for a long period and reduce or prevent the occurrence of toxic effects of substances such as H and Al and the use of fertilizers (Ronquim 2010) Therefore, the set of indicators proves to be a good tool in rural and environmental management, as it allows the consumption of inputs to be adjusted according to the immediate demands of the soil, increasing the quality of an entire agricultural ecosystem affected by a production system.

The combination of the results of the sum of bases, saturation by bases and nutrient indices makes it possible to verify the nutrient availability capacity and the need to increase the supply or avoid adding inputs through adequate management of soil fertility and production techniques, essential to avoid greater nutrient losses, such as crop rotation (Chahal et al. 2021; D'Acunto et al. 2018; King and Blesh 2018) and addition of organic fertilizers (Han et al. 2021; He et al. 2022), for example. The supply and replacement of nutrients are directly related to the soil's capacity to retain them (Ronquim 2010), therefore, soil fertility and management are directly related to many of the main agricultural environmental issues, especially those related to input consumption by production systems. Furthermore, correctly adjusted soil chemical parameters increase the efficiency of land use, preventing poorly supplied crops from delaying development and leaving the soil exposed to the climate for longer, which can lead to degradation of the soil's chemical properties, thus, compromising future production, in addition to reducing the carbon stock and favoring surface runoff, actions that increase impacts on the environment (Bolliger et al. 2006; Steinmetz et al. 2016).

LCA and soil quality indicators

LCA, considered one of the most promising methodologies for environmental assessment of complex production systems, can integrate the three emissions compartments for ecosystem—soil, water, and air—in the same study, however it does not yet have methods or standardized tools to assess soil quality. As we can see in the report Global Guidance on Environmental Life Cycle Assessment Indicators, v. 2, from the United Nations Environmental Program (UNEP 2019), publications that recommend methods and indicators to be used in LCA studies, do not offer any alternative to evaluate impacts related to the chemical quality of the soil. In the report, soil quality is linked to the quality of ecosystem services, which provides limited and provisional recommendations to evaluate certain parameters related to soil quality. In material, soil quality is associated with physical, chemical, and biological properties, which can be stressed when achieved through changes in land use and the presence and/or accumulation of contaminants, which makes the assessment of soil practices and management soil through the inclusion of soil quality indicators, essential for LCA studies of production systems that transform or occupy soil.

In the section where the authors of the guide analyze existing methods for assessing life cycle impacts (LCIA) through available characterization factors (CF)—in the characterization stage of an LCA, elementary flows are translated into contributions to impact categories through characterization factors. In the context of environmental dissipation, the characterization factor is the environmental dissipation potential for an element (van Oers et al. 2020)—relevant to soil quality, they state that currently available models for LCIA do not provide a comprehensive and harmonized assessment of soil quality. A recommended model is LANCA® (Bos et al. 2016), however, focused on approaches to physical soil quality parameters, such as groundwater regeneration, mechanical filtration, and water infiltration capacity.

The soil chemical quality indicators for LCIA that have been most debated and studied are those related to changes in SOC stock (Mattsson et al. 1990; Cowell 1998; Baitz et al. 1998; Mila i Canals and Polo 2003; Mila i Canal et al. 2007; Brandao and Mila i Canals 2013), being treated in the guide as the main alternative to the publication by Brandao and Mila i Canals (2013). Other soil quality parameters covered in the guide are biomass loss, erosion, infiltration capacity, among some others, which are not chemical parameters directly linked to soil fertility. According to UNEP (2019) due to all the limitations of existing LCIA models, SOC remains the only available indicator that is broadly linked to several soil quality functions and is applicable within the scope of LCIA, although it is recognized that SOC does not represent all aspects of soil quality.

Although there are studies committed to advancing the topic, as those mentioned in the UNEP report (2019) and other relevant studies such as those by Alvarenga et al. (2015), Joensuu and Saarinen (2017), Guarrigues et al. (2013), Oberholzer et al. (2012), Saad et al. (2013) and Vidal Legaz et al. (2017), all present different proposals, which are inconsistent with each other or which fail to evaluate soil quality as expected in an LCA study, in addition to the majority evaluating only physical parameters or those related to soil cover.

Furthermore, the preferable way to evaluate environmental impacts in LCA studies is through the ability to incorporate all information from a production system at inventory level, and thus be evaluated together with it. However, for this, in addition to the need for methods or techniques to obtain information at inventory level, there is a demand for CFs that allow inventory results to be integrated into the appropriate impact categories, which is a major challenge when evaluating soil quality, as there are few known alternative methods and/or current indicators capable of being incorporated into LCA at this level. For the authors of the UNEP report (2019), the incorporation of soil quality impacts into the LCA should ideally involve the choice of indicators that should comply with the following criteria: (i) soil quality should be represented by a minimum number of indicators, in order to avoid the multiplication of recommended indicators, with casual legations to the main functions of the soil to allow an efficient interpretation of impacts; (ii) the indicator must be compatible with existing LCI land use flows, that is, flows elementary to land occupation and transformation, but can also recommend additional elementary flows; (iii) the indicator must be applicable globally, to all types of land use, both for background and foreground processes.

The great difficulty in this transformation is due to the complexity of determining how soil properties and functions influence system functions (for example, productivity and land use) and then reflecting them in functional units. According to Vidal Legaz et al. (2017), among the methods evaluated in their study, those that had better applicability for LCA (the easiest to be adapted as CF) were those with less relevance and comprehensibility, while those with reduced applicability for LCA (the most difficult to be adapted as CF) were those with greater scientific relevance and comprehensibility. Furthermore, the LCA methodology is also unable to classify agricultural practices as "good or bad", reducing the assistance to the management of practices to mitigate impacts, which could be improved using quantitative tools that provide information that also has qualitative applicability (Vida Legaz et al. 2017). However, as LCA is a highly quantitative methodology, it is unable to include qualitative information at the LCI level and can only do so through support tools. Furthermore, soil functions must be addressed through its pedoclimatic variables, such as soil texture, organic matter, precipitation, temperature, and related biological parameters, in addition to requiring a geographic scale that is sensitive to such variables and provides optimal quality. of the soil at a given time. Thus, as stated in the UNEP report (2019), there is currently a limited number of LCIA models that cover a series of impact pathways that address soil quality issues, but there is still no comprehensive approach to assessing soil quality, mainly aspects related to chemical fertility.

Due to such challenges and technical limitations, in this study we adopted the recommendations of Vidal Legaz et al. (2017) and Garrigues et al (2013) who state that due to the difficulty in developing soil quality indicators capable of being included in ICV, which at least the soil parameters be assessed using conventional EIA methods and treated separately from the impact categories assessed by LCA, avoiding neglecting impacts and thus gathering useful information that contributes to the discussion and development of models considered more in line with the LCA methodology.

By contextualizing the use of soil chemical quality indicators to that of LCA, we ensured that the different results interacted and complemented each other. In this way, it can be seen that the indicators contributed efficiently to the assessments of impacts of agricultural production systems by providing information about the environment (the soil), allowing to improve the understanding of impacts and mainly contributing to the management of the use of inputs and of agricultural operations. Thus, the inability of the LCA to classify agricultural practices as "good or bad" and assist in the management and mitigation of impacts, was reduced with the participation of indicators from the APOIA-NovroRural method, including providing comprehensive information at the level of interest to managers and farmers, allowing them to check whether soil management is being practiced appropriately and which options to adopt to create a more sustainable environment for local conditions.

The interaction between the methodologies applied in this study points to the importance of maintaining soil fertility as a key factor in mitigating types of impacts considered strategic to the agricultural sector. We noticed through the LCA evaluations that the production systems that consumed the most fertilizers showed a strong relationship between the use of inputs and the impacts in the main categories evaluated. At the same time, the indicators point out that the problem is not only in the consumption of fertilizers, but also in the degradation of soil fertility parameters, such as the high presence of H + Al and the decrease in CEC levels. The lower quality of these parameters indicates interference in the availability and use of nutrients, and maintaining the quality of such parameters would promote more efficient use of fertilizers without affecting, or even reducing, the need for their import. LCA applied alone is not yet capable of achieving such results, making indicators interesting tools for expanding the amount of information about the environment and the impacts and management of agricultural ecosystems. Future studies can start from this premise and advance new models that transform the impacts on the chemical quality of the soil into environmental emissions, and subsequently, these into characterization factors for LCA.

Conclusion

Firstly, this study indicates the need to continue carrying out assessments to develop and enable the use of chemical soil quality indicators for LCA, as it is currently the least explored class of soil quality indicators. Furthermore, this information can guide the adoption of more sustainable production strategies, reconciling acceptable productivity with environmental preservation, which can also be applied to policy decisions.

In the case study, it was found that the farms that presented the best results through soil quality indicators were those that best managed the fertility of their soils through agricultural techniques and more adequate replacement of nutrients. The indicators were useful to provide important information for the environmental management of the activities of agricultural production systems in all impact categories. LCA confirmed the use of fertilizers among the activities that most influenced the performance of the impact categories that most impacted, per unit: Climate change (kg CO_2 eq.); Terrestrial ecotoxicity (kg 1,4-DCB); and Human toxicity, non-carcinogenic (kg 1,4-DCB). Thus, soil quality management can reduce environmental impacts in highly relevant impact categories, particularly by supporting fertilizer use management. Therefore, the application of the APOIA-NovoRural indicators together with the LCA can relate and provide important information for the management of soil quality, the quantity of supplied inputs and, consequently, the environmental performance of production systems.

Hence, the innovation of this study is demonstrating that the use of soil chemical quality indicators in conjunction with LCA is essential to improve its evaluations and information level. Furthermore, a better understanding of impacts on soil quality would improve the environmental efficiency of agriculture without the necessity to increase or even reduce the use of inputs without affecting productivity. Information that until now the LCA methodology applied alone has not been able to achieve.

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Author contributions Dr. KRGL coordinated the study and worked at all stages of development. Dr. MUV together with Dr. RR, professors of University of Londrina, helped coordinate the study and worked at all stages of development. Dr. HD and Dr. JCFDS, specialists in soil, fundamental to the study, they provided the areas, collection team and laboratory for soil analysis, in addition to assisting in the use of their knowledge about soil sciences. Dr. MISF-M, specialist in the use of LCA for agriculture, helped us in using the methodology.

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Availability of data and materials It is stated here that all the study data, as well as each step that was applied to obtain them, are available in the text, mainly in the topics of methods and supplementary material (for the results of the soil analysis). In case of questioning, the corresponding author is available to provide more information.

Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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