Experimental Agriculture (2023), vol. 59, e18, 1–17
doi:10.1017/S0014479723000145

RESEARCH ARTICLE

Sustainability assessment methodology oriented to soil-associated agricultural experiments

Oscar Iván Monsalve Camacho[1], Oscar Gonzalo Castillo-Romero[2], Carlos Ricardo Bojacá Aldana[3] and Martha Cecilia Henao Toro[4]

[1]Programa de Ingeniería Agronómica, Universidad de Ciencias Aplicadas y Ambientales, Bogotá, Colombia, [2]Agricultural & Biological Engineering Department and the Institute for Sustainable Food Systems, University of Florida, Gainesville, FL, USA, [3]Department of Basic Sciences and Modelling, Universidad Jorge Tadeo Lozano, Bogotá, Colombia and [4]Agricultural Sciences Faculty, Universidad Nacional de Colombia, Bogotá, Colombia
Corresponding author: Oscar Iván Monsalve Camacho; Email: omonsalve@udca.edu.co

(Received 29 June 2022; revised 13 July 2023; accepted 16 August 2023)

Summary
A variety of established tools are available for agricultural sustainability assessment at global, regional, and farm geographical scales. However, no assessment has been reported in research literature to indicate their ability to provide insights about the most sustainable cropping system at plot level or experimental unit. Despite the environmental and social importance of soil in agricultural systems, many of the sustainability assessments use few or no indicators related to soil properties or processes. Hence, we propose a sustainability assessment methodology oriented to soil-associated agricultural experiments (SMAES) by defining its parameters through simulations and testing the methodology with real data from a fertilization tomato experiment with five treatments: chemical control (CR); organic control (OR); and organic: chemical ratios (OR) of 25:75, 50:50, and 75:25. The distance from the maximum, principal component analysis, and product of weighted indicator techniques were chosen for normalization, weighting, and aggregation in a single index process, respectively. Applying the SMAES methodology, the sustainability level of the treatments followed this sequence: CR (0.95) > O25:C75 (0.73) > O50:C50 (0.60) > O75:C25 (0.55) > OR (0.45). The proposed SMAES methodology allows soil researchers to define the best treatment through the interaction of the environmental, social, and economic dimensions of agricultural systems.

Keywords: fertilization; life cycle assessment; soil quality; sustainability assessment tools; sustainability indicators

Introduction

The goal of most applied experimental research in agricultural soil management is to find the treatments that cause the highest crop yield. However, most cropping system improvements and adaptations are originated by farmers rather than experimental stations or test plots (Adhikari *et al.*, 2018). This is because the research knowledge transferred to farmers often does not consider the multiple factors influencing agricultural systems. Experimental research recommends that the treatments should be evaluated on statistically significant differences of a few response variables. However, the technical optimum usually does not correspond to the economic optimum (Lanfranco and Helguera, 2006), and the interaction among the environmental, social, and economic dimensions may not be considered in experiments based on yield evaluations and environmental impact or profitability variables (e.g., Gu *et al.*, 2018; Wang *et al.*, 2018).

Pretty *et al.* (2010) examined strategies to establish a consensus in developing and testing metrics of sustainability in different agricultural systems that are appropriate and acceptable to several agroecological, social, economic, and political contexts. To perform agricultural

Table 1. Normalization and aggregation techniques evaluated

	Technique	Abbreviation	Equation
Normalization	Standard deviation from the mean	N1	$V' = \frac{V - V_x}{S_d}$
	Distance from the maximum	N2	$V' = \frac{V}{M_A}$
	Distance from the average	N3	$V' = \frac{V}{V_x}$
	Distance from extreme observed values	N4	$V' = \frac{V - V_{min}}{V_{max} - V_{min}}$
Aggregation	Weighted sum of indicators	IS_S	$IS_S = \sum_{k=1}^{k=n} W_k \times I_k$
	Product of weighted indicators	IS_P	$IS_P = \prod_{k=1}^{k=n} {I_k}^{W_k}$
	Multicriterion function	IS_λ	$IS_\lambda = (1-\lambda)*[Min_k(W_k*I_k)] + \lambda * \sum_{k=1}^{k=n} W_k*I_k$

V´ = normalized value, v = observed value to normalize, v_x = average of all observed values, S_d = standard deviation, M_A = more sustainable value of the data set, v_{min} = minimum observed value, v_{max} = maximum observed value, IS_S = sustainability index for weighted sum, W_k = weight associated to the indicator k, I_k = standard value of indicator k, Min_k ($W_k * I_k$) = weighted and normalized minimum value for the set of indicators. Five values of the compensation parameter are considered (λ = 0.00, 0.25, 0.50, 0.75, and 1.00). Twenty randomized values (v), from 93 to 140, were used to the normalization simulations.

sustainability assessments, tools (metrics) have focus on evaluating the sustainability of traditional production systems already established (e.g., Afshar and Dekamin, 2022; Akinnifesi *et al.*, 2006; Astier *et al.*, 2011; Moore *et al.*, 2014; Starkl *et al.*, 2022; Uphoff, 2003; Van Asselt *et al.*, 2014; van der Vossen, 2005). However, to date, there are no tools to assess the sustainability of the treatments (cropping systems) evaluated through experimentation. Deytieux *et al.* (2016) stated that sustainability assessments should be oriented to new crop alternatives developed through experimentation or modeling. These assessments will allow farmers to adopt the recommendations and leading public science to become proactive rather than reactive (Pretty *et al.*, 2010).

Considering that key soil functions in the ecosystem allow essential provision, regulation, culture, and support services (Adhikari and Hartemink, 2016) and the impact of production strategies depends on the soil, many of the agricultural sustainability assessments use few or no indicators related to soil properties or processes (e.g., Gómez-Limón and Sanchez-Fernandez, 2010). According to Van Asselt *et al.* (2014), no more than one indicator per dimension is necessary to carry out agricultural sustainability assessments. In this context, there may be a case where no indicator related to the soil is evaluated. However, Aloui *et al.* (2022) stated that soil researchers need a tool to estimate the level of sustainability of experimental treatments through a quantitative index.

The objective of this work was to propose the Sustainability Assessment Methodology Oriented to Soil-Associated Agricultural Experiments (SMAES) that estimates the sustainability level through a quantitative index. This methodology has three essential features: (i) it can be adapted to experiments related to soil management with different spatial, temporal, and measurement characteristics; (ii) it can be used in experiments with broad or limited access to indicators; and (iii) it is quantifiable, in terms of sustainability index for the treatments under consideration.

To know the functionality of SMAES in possible scenarios, we built SMAES from hypothetical data and tested it with data from a real experiment.

Materials and Methods

Normalization, weighing, selection, and aggregation techniques with hypothetical data

The most common process to build sustainability indices includes normalization, weighting, and aggregation (Gomez-Limón and Sánchez-Fernandez, 2010). According to that, we evaluated different techniques for each of those processes to find the best fit with SMAES. Four normalization techniques were evaluated according to Freudenberg (2003), as shown in Table 1.

https://doi.org/10.1017/S0014479723000145 Published online by Cambridge University Press

The techniques for allocating weights to the indicators can be divided into positive and normative: Positive or endogenous are techniques that use statistical procedures. Principal components analysis (PCA) is one of the most used. In this sense, PCA approach suggests computing the sum of the square coordinates of an indicator k in each eigenvector (λ_j) multiplied by the percentages of total variability (f_j) explained by each principal component (PC) used as a weighting factor or weighting (W_k) to rate the indicators (Rossi *et al.*, 2009), as shown below.

$$W_k = \sum_{j=1}^{PC} \lambda_j \times PC_j \tag{1}$$

in which W_k corresponds to each attribute. Each W_k indicates the weight of the selected indicator representing the attribute. The higher the W_k, the more important the contribution of the attribute.

Normative or exogenous techniques try to allocate different weights to the indicators as a function of expert knowledge, assuming sustainability as a social construction (Baush *et al.*, 2014; Gómez-Limón and Sanchez-Fernandez, 2010; OECD-JRC, 2008).

The indicator selection method developed by Monsalve and Henao (2022) was included in SMAES. In summary, this method divides the indicators according to their hierarchy (raw, baseline, and core indicators). The minimum indicators set (MIS) is defined according to the compliance of the different types of criteria (mandatory, main, alternative non-mandatory, and correlation) and the score obtained through a checklist. Indicators in the MIS represent each attribute and dimension in SMAES.

Through simulations of a range of real possible responses, three aggregation techniques were evaluated (Table 1) to determine which one has the best representation of reality. To perform the simulations, the three dimensions of sustainability (I_k) were assumed with three different possible values each, as follows: $I_1 = 0.00, 0.33, 1.00$; $I_2 = I_3 = 0.10, 0.33, 1.00$. Each possible combination of I_k was contrasted with a weight vector (W_k), with four combinations of factors (W_1, W_2, W_3) = {(0.33, 0.33, 0.33), (0.1, 0.1, 0.8), (0.1, 0.8, 0.1), (0.8, 0.1, 0.1)}. Each value of W_k is assigned to each value of I_k, building four scenarios with 27 combinations I_kW_k each (Table 2).

Evaluation of SMAES with experimental results

The study was carried out in the Bio-Systems Center of the Jorge Tadeo Lozano University, located in Chía (Cundinamarca, Colombia). A randomized complete block design with five treatments and 15 experimental units (EU) – three repetitions per treatment - was established. Five treatments or mixtures of organic and chemical fertilization in different proportions were evaluated, as follow: chemical control (CR); organic control (OR); organic:chemical ratio 25%–75% (O25:C75); 50%–50% (O50:C50); 75%–25% (O75:C25). One-hundred percent organic pre-planting fertilization formula was composed of: 2600 g m^{-2} of chicken manure compost, 180 g m^{-2} of phosphoric rock, and 6 g m^{-2} of manganese sulfate. One-hundred percent chemical pre-planting fertilization formula was composed of: 50 g m^{-2} of ammonium sulfate, 65 g m^{-2} of diammonium phosphate, 4 g m^{-2} of manganese sulfate, and 0.5 g m^{-2} of boron.

SMAES requires the construction of one production system inventory (PSI) for each EU. With the PSI, some environmental and social indicators and all economic indicators are estimated. In the PSI, all agricultural exploitation and resource consumption data (inputs, labors, and outputs) were collected (data shown in supplementary material). Regarding the indicators management, Table 4 shows the indicators selected (core indicators) for analysis with SMAES. Characteristics of all raw indicators can be seen in Monsalve and Henao (2022). To define the core indicators, we adopted the method for selection of indicators proposed by Monsalve and Henao (2022). In summary, this method divides the indicators according to their hierarchy (raw, baseline, and core indicators). The MIS is defined according to the compliance of the different types of criteria (mandatory, main, alternative non-mandatory, and correlation) and the score obtained through a

Table 2. Simulations designed to find the best aggregation technique

		Simulation 1			Simulation 2			Simulation 3			Simulation 4		
		W_k											
		W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
		0.33	0.33	0.33	0.1	0.1	0.8	0.1	0.8	0.1	0.8	0.1	0.1
		I_1W_1	I_1W_2	I_1W_3	I_1W_1	I_1W_2	I_1W_3	I_1W_1	I_1W_2	I_1W_3	I_1W_1	I_1W_2	I_1W_3
I_k	I_1	0.0 0.33 0.3 0.33 1.0 0.33	0.3 0.33 1.0 0.33 0.0 0.33	1.0 0.33 0.0 0.33 0.3 0.33	0.0 0.1 0.3 0.1 1.0 0.1	0.3 0.1 1.0 0.1 0.0 0.1	1.0 0.8 0.0 0.8 0.3 0.8	0.0 0.1 0.3 0.1 1.0 0.1	0.3 0.8 1.0 0.8 0.0 0.8	1.0 0.1 0.0 0.1 0.3 0.1	0.0 0.8 0.3 0.8 1.0 0.8	0.3 0.1 1.0 0.1 0.0 0.1	1.0 0.1 0.0 0.1 0.3 0.1
		I_2W_1	I_2W_2	I_2W_3	I_2W_1	I_2W_2	I_2W_3	I_2W_1	I_2W_2	I_2W_3	I_2W_1	I_2W_2	I_2W_3
	I_2	0.1 0.33 0.3 0.33 1.0 0.33	0.3 0.33 1.0 0.33 0.1 0.33	1.0 0.33 0.1 0.33 0.3 0.33	0.1 0.1 0.3 0.1 1.0 0.1	0.3 0.1 1.0 0.1 0.1 0.1	1.0 0.8 0.1 0.8 0.3 0.8	0.1 0.1 0.3 0.1 1.0 0.1	0.3 0.8 1.0 0.8 0.1 0.8	1.0 0.1 0.1 0.1 0.3 0.1	0.1 0.8 0.3 0.8 1.0 0.8	0.3 0.1 1.0 0.1 0.1 0.1	1.0 0.1 0.1 0.1 0.3 0.1
		I_3W_1	I_3W_2	I_3W_3	I_3W_1	I_3W_2	I_3W_3	I_3W_1	I_3W_2	I_3W_3	I_3W_1	I_3W_2	I_3W_3
	I_3	0.1 0.33 0.3 0.33 1.0 0.33	0.3 0.33 1.0 0.33 0.1 0.33	1.0 0.33 0.1 0.33 0.3 0.33	0.1 0.1 0.3 0.1 1.0 0.1	0.3 0.1 1.0 0.1 0.1 0.1	1.0 0.8 0.1 0.8 0.3 0.8	0.1 0.1 0.3 0.1 1.0 0.1	0.3 0.8 1.0 0.8 0.1 0.8	1.0 0.1 0.1 0.1 0.3 0.1	0.1 0.8 0.3 0.8 1.0 0.8	0.3 0.1 1.0 0.1 0.1 0.1	1.0 0.1 0.1 0.1 0.3 0.1

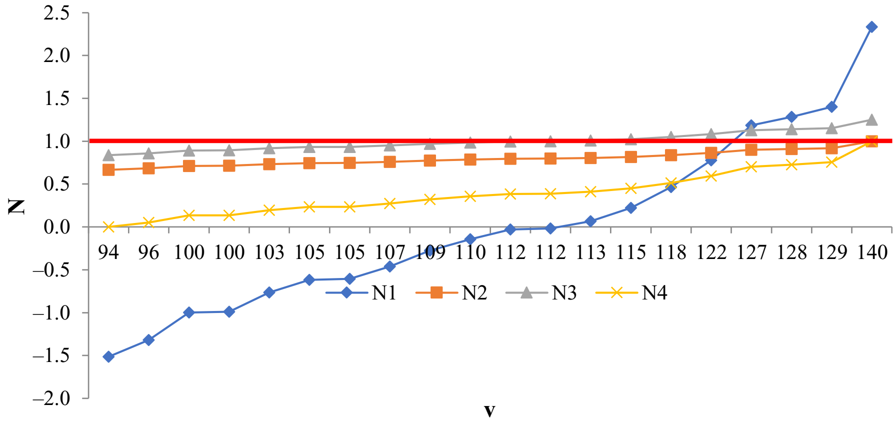

Figure 1. Comparison of normalization techniques: N1 = standard deviation from the mean; N2 = distance from the maximum; N3 = distance from the average and N4 = distance from extreme observed values; v = observed values. Average = 112; standard deviation = 12; maximum = 140; minimum = 94. Horizontal red line allows visualization of those normalization techniques that generate values above one (1).

checklist. Indicators in the MIS represents each attribute and dimension in SMAES (Monsalve and Henao, 2022).

Results

Evaluation of SMAES with hypothetical data: selection of normalization method

After comparing the four normalization techniques, the distance from the maximum (N2) was chosen to be used in SMAES. Standard deviation from the mean (N1) and distance from the average (N3) generate values outside the established range (0 to 1). Distance from extreme observed values (N4) assigns a value of 0 to the lowest observed value. This causes inconsistences with the aggregation technique since zero implies absolute unsustainability and should not occur even with the lowest observed values (Fig. 1).

Evaluation of SMAES with hypothetical data: selection of weighing technique

Positive or endogenous techniques (e.g., PCA) are widely used showing a good fit for the plot or EU scale (Dong *et al.*, 2015; Gómez-Limón and Sanchez-Fernandez, 2010; Rossi *et al.*, 2009). PCA is a method that allocates weights to attributes objectively (Rossi *et al.*, 2009), which is advantageous for the geographical evaluation scale (plot or EU) of the SMAES. At this scale, the three dimensions of sustainability depend on agricultural activities rather than government policies. Normative or exogenous technique requires surveys to obtain the opinion of experts. In this sense, the researcher should (i) define the minimum viable and reliable number (statistically) of experts to contact, (ii) design the survey, (iii) rely upon experts to respond, (iv) rely upon researchers to both carry out the survey, and (v) analyze the results. This survey technique works well for large-scale studies whose results impact a considerable population, but it can be very costly and unfeasible to carry out at the plot or experimental unit scale.

Evaluation of SMAES with hypothetical data: selection of aggregation technique

The performance of IS_P and $IS\lambda_{0.00}$ with the four possible weighting forms revealed the result is zero when at least one of the I_k is 0, regardless of W_k (Fig. 2). Unlike IS_P and $IS\lambda_{0.00}$, the IS_S and $IS\lambda_{1.00}$ indices (which generate the same result) tend to compensate for the effect of

https://doi.org/10.1017/S0014479723000145 Published online by Cambridge University Press

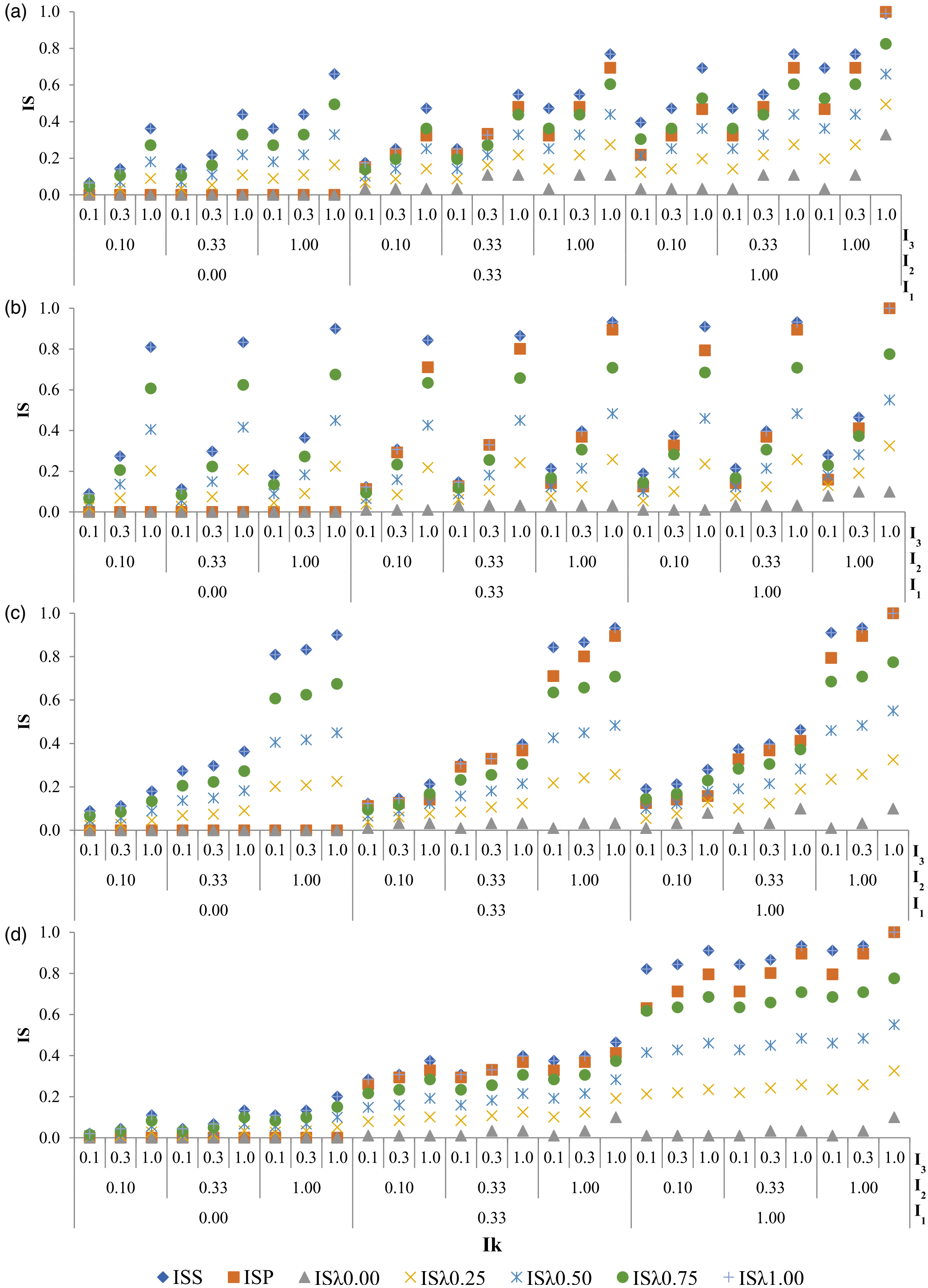

Figure 2. Simulation of indicators (I_k) and weights. (a) $W_1 = W_2 = W_3 = 0.33$, (b) $W_1 = 0.1$, $W_2 = 0.1$, $W_3 = 0.8$, (c) $W_1 = 0.1$, $W_2 = 0.8$, $W_3 = 0.1$, (d) $W_1 = 0.8$, $W_2 = 0.1$, $W_3 = 0.1$ for the proposed sustainability indices (IS): IS_S = weighted sum of indicators, IS_P = product of weighted indicators, and IS_λ = multicriteria function for $\lambda = 0.00, 0.25, 0.50, 0.75$, and 1.

https://doi.org/10.1017/S0014479723000145 Published online by Cambridge University Press

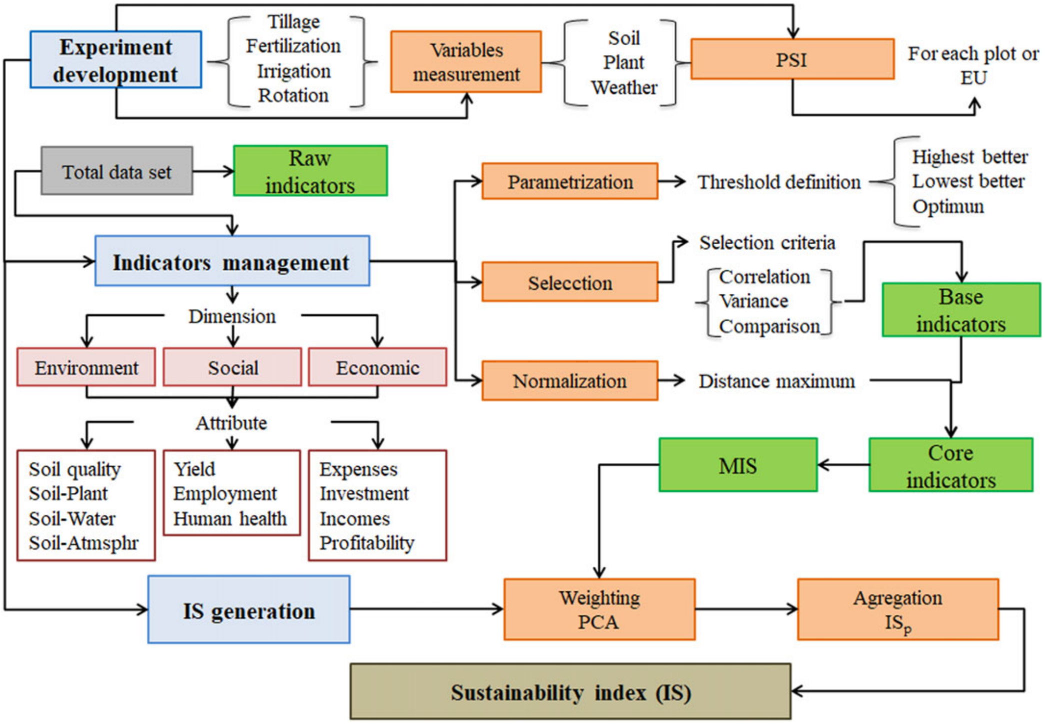

Figure 3. Synthesis of the sustainability evaluation methodology oriented to agricultural experiments associated with soil (SMAES). The blue, green, orange, gray, and brown boxes indicate macro-processes, achievements, activities, data organization, and outcome (IS), respectively. PSI = production system inventory; EU = experimental unit; MDS = minimum data set; PCA = principal component analysis; IS_p = product of weighted indicators.

indicators with values close or equal to zero. It is important to define the notion of 'compensation'. In this context, compensation is the action of masking the effect of an indicator, attribute, or dimension that is outside the optimal range with another that is within the optimal range. For instance, for $W_{1-2-3} = (0.33, 0.33, 0.33)$ (Fig. 2a), when $I_1 = 0$, IS_P and $IS\lambda_{0.00} = 0$, while IS_S and $IS\lambda_{1.00} = 0.07$ to 0.66. In this case, the total compensation effect between indicators is observed for IS_S and $IS\lambda_{1.00}$. There is no evidence of any combination for W_k that result in zero for IS_S and $IS\lambda_{1.00}$.

Whenever $I_1 = I_2 = I_3 = 1$, independent on any combination of W_k, then $IS_P = 1$ (Fig. 2). IS_P also applies compensation between indicators, although the compensation rate between indicators is not constant. It varies depending on the value of the indicators and the weights. Thus, as any indicator increases, the same applies to its compensation capacity and vice versa. Except for IS_P and $IS\lambda_{0.00}$, all IS values increased proportionally with the increase of I_k and W_k. This increase is more prominent when ($I_1 = 0$; $W_k = 0.1$) (Fig. 2b, c). In Fig. 2d, if [$I_1 = 0$, $W_k = 0.8$], all IS are very low and increase as I_1 rises to 0.33, and finally to 1. When analyzing the intermediate levels of compensation ($IS\lambda_{0.25}$, $IS\lambda_{0.50}$, and $IS\lambda_{0.75}$), IS_λ generated higher values as the degree of compensation increased.

Based on these results, the weighted indicator product technique (IS_P) provides sufficient representation of the objective and subjective process of the analysis which is best suited for SMAES. This is because the same equation represents the total, partial, and null compensation.

SMAES summary

Figure 3 shows a scheme that summarizes the methodology of sustainability evaluation oriented to agricultural experiments associated with soil (SMAES) divided into three macro-processes:

https://doi.org/10.1017/S0014479723000145 Published online by Cambridge University Press

(1) Experiment development (tillage, fertilization, irrigation, or rotation) during which the measurement of soil, plant, and climate variables are taken, and the PSI is constructed individually for each EU or plot and (2) the entire data set (variables or raw indicators) is divided according to the dimension (environmental, social, or economic) and attribute to which it belongs. Subsequently, (i) each indicator is parameterized by defining the thresholds (whether there is an optimum or this optimum is the highest or lowest value in the dataset), (ii) a correlation, variance, and comparison analysis is performed to define the base indicators, (iii) which are normalized, and (iv) each base indicator goes through the checklist of selection criteria to define the core indicators and subsequently the MIS; (3) build the sustainability index (IS), where weights are assigned to each core indicator (weighting) by PCA. The indicators are added using the product of weighted indicators technique (IS_p) to obtain the IS value.

Evaluation of SMAES with experimental results: minimum indicators set (MIS)

As mentioned in the Materials and Methods section, indicator selection process was based on the method developed by Monsalve *et al.* (2022). As shown in Table 3, the minimum indicator set (MIS) was made up at the environmental dimension from the core indicators soil quality indicator using principal component analysis (SQ_{PCA}), with a score of 0.81; land use (LU) (0.68); potential eutrophication (PE) (0.75); and global warming potential (GWP) (0.73). For the social dimension, MIS came from the core indicators yield (Yd) (0.77); wages per year per hectare (JA) (0.77); and human toxicity (HT) (0.68). Finally, for the economic dimension, MIS was built from the core indicators variable costs (VC) (0.81); net incomes (NI) (0.81); and benefit-cost ratio (B/C) (0.82) (Table 3). From 30 raw indicators (13 environmental, 7 social, and 10 economic), 10 core indicators were chosen (4 environmental, 3 socials, and 3 economics) (Table 4).

Evaluation of SMAES with experimental results: weighting, comparing treatments, and estimation of IS

Weights (W_k) were allocated similarly for all attributes indicating that, in this case, all dimensions had a similar influence on sustainability (Table 5). CR showed the best results for the core indicators of all dimensions. On the other hand, OR had the lowest values because of its lowest income (NI) and yield (Yd). At the same time, OR needed a higher area (LU) to produce the same amount of produce as CR (Table 6). CR showed the highest economic sustainability index (Fig. 4). This is due to the relationship among Yd, VC, and NI (Table 6). The opposite occurred with OR, which reported the lowest index (Fig. 4), incurring in higher costs with lower income (Table 6). A similar outcome was seen for the environmental and social dimensions, with CR being the most sustainable treatment and OR the least one (Fig. 4). Considering the three dimensions altogether, the CR treatment showed the highest sustainability index followed by O25:C75 (Fig. 4).

Discussion

Simulation process: indicators

SMAES integrates the three dimensions of sustainability (environmental, social, and economic) to define the best treatments evaluated in soil-associated agricultural experiments. To use SMAES, the first step is to select the indicators. The environmental indicators collected in this study consider the impact of soil management and the cropping system on the entire ecosystem, i.e., on biota, water, atmosphere, humans, and the soil itself. It is composed by four attributes: soil quality, soil–plant, soil–water, and soil–atmosphere (Monsalve *et al.*, 2021a). These attributes search for a sustainable environmentally management of the soil, i.e., not performing any irreparable negative effect either to the soil itself or to any other ecosystem (Tóth *et al.*, 2018). A considerable number of indicators can be measured either in the field or lab; however, the number of indicators must be

Table 3. Score obtained by the raw indicators for the mandatory

		MnTr								NmMn							NmAt						CrLc		
								W_{CS}							W_{CS}						W_{CS}		W_{CS}		
Atrib	Ind.	StOb	QuAt	SpLn	TrSt	NoRd	SgDf	0.5		AfMs	PrTz	MsEd	ObSt	VrRt	0.2		AcTn	PtDv	PrFu	AgGt	0.2		0.1		Tt
Environmental dimension																									
Soil qual	SQ_{SMAF}	2	1	1	1	1	0	0.0		3	0	2	2	1	0.7	0.15	2	1	1	1	1.0	0.20	1.0	0.10	0.00
	SQ_{SA}	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	2	0	1	1	0.8	0.16	0.7	0.07	0.78
	SQ_{W}	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	2	0	1	1	0.8	0.16	0.7	0.07	0.78
	SQ_{PCA}	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	2	0	1	1	0.8	0.16	1.0	0.10	0.81
Soil plant	LU	2	1	1	1	1	2	0.7	0.36	3	0	2	1	1	0.6	0.13	2	0	1	0	0.6	0.12	0.7	0.07	0.68
	W-kg	2	1	1	1	1	2	0.7	0.36	3	0	0	1	1	0.5	0.09	1	0	1	0	0.4	0.08			0.00
	N-kg	1	1	1	1	1	2	0.6	0.32	3	0	2	2	1	0.7	0.15	1	0	1	0	0.4	0.08	1.0	0.10	0.64
Soil water	FWT	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	MWT	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	PE	2	1	1	1	1	5	1.0	0.50	2	0	0	1	1	0.4	0.07	2	0	0	0	0.4	0.08	1.0	0.10	0.75
Soil atmos	PA	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	GWP	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	2	0	0	0	0.4	0.08	1.0	0.10	0.73
	OLD	1	1	1	1	1	5	0.9	0.45	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
Social dimension																									
Food secur	Yd	2	1	1	1	1	2	0.7	0.36	3	0	2	2	1	0.7	0.15	2	1	1	0	0.8	0.16	1.0	0.10	0.77
	PCat	2	1	1	1	1	0	0.0		3	0	2	2	1	0.7	0.15	1	0	0	0	0.2	0.04			0.00
Empl gen	JA	2	1	1	1	1	5	1.0	0.50	1	0	2	0	0	0.3	0.05	2	0	1	0	0.6	0.12	1.0	0.10	0.77
Hum health	EL_{B}	2	1	1	1	1	5	1.0	0.50	3	0	0	0	1	0.4	0.07	0	0	0	0	0.0	0.00	1.0	0.10	0.67
	$EL_{B(4,5)}$	2	1	1	1	0	5	0.0		3	0	0	0	1	0.4	0.07	0	0	0	0	0.0	0.00	0.3	0.03	0.00
	PO	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	HT	2	1	1	1	1	5	1.0	0.50	2	0	0	1	1	0.4	0.07	1	0	0	0	0.2	0.04	0.7	0.07	0.68
Economic dimension																									
Expen	VC	2	1	1	1	1	5	1.0	0.50	1	0	2	1	1	0.5	0.09	1	1	1	0	0.6	0.12	1.0	0.10	0.81
	FC	2	1	1	1	1	4	0.9	0.45	1	0	2	0	0	0.3	0.05	1	1	1	0	0.6	0.12			0.00
Incom	GI	2	1	1	1	0	3	0.0		3	0	2	1	1	0.6	0.13	1	0	1	0	0.4	0.08			0.00
	NI	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	2	1	1	0	0.8	0.16	1.0	0.10	0.81
Proftbl	B/C	2	1	1	1	1	3	0.8	0.41	3	0	0	2	1	0.5	0.11	2	1	1	1	1.0	0.20	1.0	0.10	0.82
	NPV	2	1	1	1	1	3	0.8	0.41	1	0	0	2	1	0.4	0.07	2	0	1	1	0.8	0.16			0.00
	ORO	2	1	1	1	0	3	0.0		1	0	0	2	1	0.4	0.07	1	0	1	1	0.6	0.12	1.0	0.10	0.00
	IRR	2	1	1	1	1	3	0.8	0.41	1	0	0	2	1	0.4	0.07	2	0	1	1	0.8	0.16	1.0	0.10	0.74
	BPQ	2	1	1	1	1	2	0.7	0.36	1	0	0	2	1	0.4	0.07	1	0	1	1	0.6	0.12	1.0	0.10	0.66
	BPP	2	1	1	1	1	2	0.7	0.36	1	0	0	2	1	0.4	0.07	1	0	1	1	0.6	0.12	1.0	0.10	0.66

MnTr = main nonmandatory; NmMn = alternate nonmandatory; NmAt and correlation (CrLc) = selection criteria. Where StOb: related to sustainability objective; QuAt: quantifiable; SpIn: specifically interpretable; TrSt: transparent and standardized; NoRd: not redundant; SgDf: significantly different; W_{CS}: weighting value assigned for the selection criteria; AfMs: affordable measurement; PrTz: parameterized; MsEd:measured or estimated; ObSt: related to the study objective; VrRt: variable between repetitions; AcTn: acceptance; PtDv: participatory development; PrFu: present and future balance; AgGt: aggregate; and Tt: total score.

Indicators: soil management assessment framework (SQ_{SMAF}); soil quality indicator using principal component analysis (SQ_{PCA}); land use (LU); amount of water per kilogram produced (W-kg); amount of nitrogen per kilogram produced (N-kg); fresh water toxicity (FWT); marine water toxicity (MWT); potential eutrophication (PE); potential acidification (PA); global warming potential (GWP); ozone depletion (OLD); yield (Yd); percentage of first category (PCat); wages per year per hectare (JA); work effort indicator (EL_{B}); high and maximum work effort ($EL_{B(4,5)}$); photochemical oxidants (PO); human toxicity (HT); variable costs (VC); fixed costs (FC); investment (IV); gross income (GI); net income (NI); net present value (NPV); benefit–cost ratio (B/C); opportunity rate obtained (ORO); internal rate of return (IRR); breakeven point by quantity (BPQ); and breakeven point by price (BPP).

Table 4. Core indicators selected in the environmental, social, and economic dimensions

Dim	Attribute	Indicator	Abb	Unit	Thrs	Method
nvironmental	Soil quality	Soil quality indicator using principal component analysis	SQ_{PCA}	–	HVB	$SQ_{PCA} = \prod_{c=1}^{c=n} S_c^{Wc}$ Where Sc = Normalized value of the soil property (c), Wc = Weight of c. Detailed calculation is shown in Monsalve *et al.* (2021b)
	Soil–plant	Land use	LU	$m^2\ kg^{-1}$	LVB	$LU = \frac{1\ m^2}{kg\ Product}$
	Soil–water	Potential eutrophication*	PE	$kg\ PO_4^{3-}$ eq	LVB	$PE = \sum_i \left(\frac{\frac{v_i}{M_i} x \frac{No_2}{A_e}}{\frac{1}{M_{PO_4^{3-}}} x \frac{No_2}{A_p}} \right) m_i$ Where: vi = number of moles of N or P in a molecule of compound i, M = molecular mass ($kg\ mol^{-1}$); NO_2 = number of moles of O_2 consumed during algae degradation; Ae = number of moles of N or P contained in an algae molecule and mi = mass of substance 1 (kg) (Guinée *et al.*, 2004). It was estimated by LCA
Social	Soil–atmosphere	Global warming potential*	GWP	$kg\ CO_2$ eq	LVB	$GWP = \sum_i \left(\frac{{}_0^T a_i c_i (t) dt}{{}_0^T a_{CO_2} c_{CO_2} (t) dt} \right) m_i$ Where: T = time (years); ai = heating produced by the increase in the concentration of a gas i ($W\ m^{-2}\ kg^{-1}$); ci(t) = concentration of the gas i in time (t) ($kg\ m^{-3}$); and mi = mass of the substance i (kg). The corresponding CO_2 values are included in the denominator (Heijungs and Guinée, 2012). It was estimated by LCA.
	Food security	Yield	Yd	$Mg\ ha^{-1}$	HVB	———————————————
	Employment generation	Day's pay per year per hectare	JA	Day's-pay $year^{-1}\ ha^{-1}$	LVB	JA = JC X Cycles per year Where: JC = Day's pay per cycle per hectare
	Human health	Human toxicity*	HT	kg 1.4-DB eq	LVB	$HT = \sum_{i,n} HTP_{i,n} \times f_{i,n} \times m_i$ Where: HT = Characterization factor for human toxicity; fi, n = fraction of the substance i that is transported from the crop to the environmental compartment n and mi = emitted mass of each pollutant i (Antón, 2004). It was estimated by LCA.
Economic	Expenses	Variable costs	VC	$\$\ ha^{-1}$	LVB	Sum of variable costs
	Incomes	Net incomes	NI	$\$\ ha^{-1}$	HVB	$NI = GI - (VC + FC)$ Where: GI = Gross incomes; VC = Variable costs; FC = Fixed costs
	Profitability**	Benefit–cost ratio	B/C	$	HVB	$^B/_C = \frac{GI}{VC+FC}$.

where Abb = abbreviation; Thrs = threshold, HVB = highest value is the best, and LVB = lowest value is the best.

*For all indicators estimated through life cycle assessment (LCA), all resource consumption and emissions referred to a functional unit of mass of one kg of fresh commercial tomatoes. Extraction of the raw material to the farm gate was the limit of the system, i.e., an LCA from cradle to door. It was considered a single subsystem, fertilization. The background processes included the production of fertilizers, whose data for their production came from the Ecoinvent V3.4 database (Ecoinvent Center, 2017).

**The indicators of each attribute were obtained from the PSI, based on a business model, where all the technical, administrative, and management processes followed the Colombian legal framework (CCB, 2019; DIAN, 2019). All the variable costs (plant material, fertilizers, crop protection, wages, among others) and fixed costs (leasing, public services, salaries, administration, among others) associated with the production were accounted for and included in the analysis. The analysis was carried out based on the technique of investment projects assessment (Karibskii, 2003a y 2003b), assuming that production is constant for a cropping area of one hectare in each EU (project), transforming the values of each variable, of the EU area to one ha.

Table 5. Weighting indicators results through principal component analysis

	Environmenta9l (PCj)			Social (PCj)			Economic (PCj)		
Estimators	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Eigenvalues	1.643	0.548	0.003	1.330	1.051	0.355	1.455	0.940	0.002
Variability (%)	0.900	0.100	0.000	0.590	0.368	0.042	0.706	0.294	0.000
Cumulated (%)	0.900	1.000	1.000	0.590	0.958	1.000	0.706	1.000	1.000
PCj (%)	100%			62%	38%		71%	29%	
		Eigenvectors (λ_{PCj}):			[Eigenvectors (λj)]^2:				
Dimension	Attribute	λ_{PC1}	λ_{PC2}	λ_{PC3}	$\lambda 1$	$\lambda 2$	PC1 (%) x $\lambda 1$ (a)	PC2 (%) x $\lambda 2$ (b)	W_k (a + b)
Environmental	Soil-Plant	0.540	0.842	0.001	0.292		0.292		0.292
	Soil-Water	0.595	-0.383	0.707	0.354		0.354		0.354
	Soil-Atm	0.595	-0.381	-0.708	0.354		0.354		0.354
Social	Food sec.	-0.698	0.272	0.662	0.488	0.074	0.300	0.028	0.328
	Empl. Gen	0.054	0.942	-0.330	0.003	0.888	0.002	0.341	0.343
	Hum. Hlt.	0.714	0.195	0.673	0.509	0.038	0.313	0.015	0.328
Economic	Expenses	0.308	-0.951	-0.006	0.095	0.905	0.067	0.266	0.333
	Incomes	0.673	0.213	0.708	0.453	0.045	0.320	0.013	0.333
	Profitab.	0.672	0.222	-0.706	0.452	0.049	0.319	0.015	0.334

PCA. PC = Principal component; Atm = Atmosphere; Food sec = Food security; Empl. Gen = Employment generation; Hum. Hlt = Human health; Weight (W_k).

Table 6. Results for the evaluation of the indicators for each treatment dimension

	Attribute	Indicator	CR	OrC	O25:C75	O50:C50	O75:C25
Environment	Soil quality	SQ_{PCA}	8.93a	9.12a	8.93a	8.98a	9.12a
	Soil–Plant	LU	0.047a	0.053b	0.046a	0.048a	0.048a
	Soil–Water	EP	2.6E-04a	2.2E-03e	6.7E-04b	1.1E-03c	1.6E-03d
	Soil–Atmosphere	GWP	5.7E-02a	4.7E-01e	1.4E-01b	2.4E-01c	3.3E-01d
Social	Food security	Yd	211.6a	187.8b	217.8a	207.3a	208.3a
	Employ generation	JA	2.76a	2.79b	2.82e	2.81d	2.80c
	Human health	HT	0.23a	1.91e	0.58b	0.98c	1.35d
Economic	Expenses	VC	139.4a	140.1b	141.1c	140.6b	139.8b
	Incomes	NI	55.11a	27.74b	63.51a	47.19ab	51.76ab
	Profitability	B/C	1.18a	1.05b	1.22a	1.14ab	1.16ab

Same letter indicates no significant differences among treatments (Tukey, $p < 0.05$); $n = 15$.

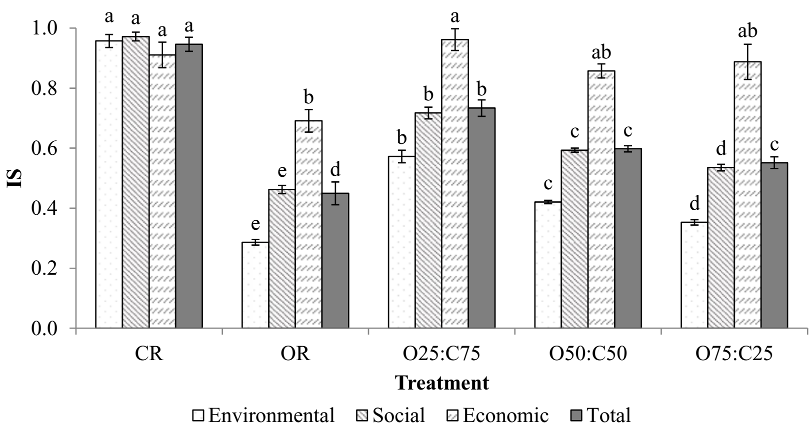

Figure 4. Comparison of sustainability indices (SI) between treatments. The SI for each dimension and the accumulated SI (Total). Equal letters indicate no significant differences between treatments (Tukey, $p < 0.05$); $n = 15$. Chemical control (CR); organic control (OR); organic:chemical ratio 25%–75% (O25:C75); 50%–50% (O50:C50); 75%–25% (O75:C25).

estimated through models, such as life cycle assessment (LCA) (Monsalve *et al.*, 2021a). In this sense, the PSI is critical to SMAES because most environmental and social indicators along with all economic indicators are based on the PSI (Monsalve *et al.*, 2021a). It is worth noting that SMAES works at the plot level, where commercial conditions are simulated, and the treatments are the only modifications to the cropping system. Experiments under fully controlled conditions may have limitations since the inventory of the production system may not be related to the commercial cropping conditions.

Many authors have pointed out the importance of establishing selection procedures with transparent and well-defined criteria that lead to relevant, comprehensive, and meaningful assessments that represent a production system (Binder *et al.*, 2010; de Olde *et al.*, 2016; Lebacq *et al.*, 2013; Marchand *et al.*, 2014). The definition and prioritization of the criteria to make the selection of the indicators vary widely among the assessment tools. Therefore, it is necessary to describe these criteria by adding clarity and reliability to the sustainability assessments (de Olde *et al.*, 2016). The indicators selection procedure included in SMAES (Monsalve and Henao, 2022) allows the user to choose the suitable indicators given a list of criteria grouped in hierarchical categories (raw, baseline, and core indicators). It is possible and highly recommended to use this procedure both before the experiment development and during the analysis.

https://doi.org/10.1017/S0014479723000145 Published online by Cambridge University Press

Simulation process: IS selection

Munda (2005) suggests the use of noncompensatory multicriteria techniques ($IS\lambda_{0.00}$) for the elaboration of sustainability indices. These techniques do not allow indicators with low values to be compensated by those with higher values validating the concept of 'strong' sustainability, which implies the impossibility of replacing the effect of one indicator or dimension by another. However, if quantitatively zero corresponds to unsustainable and one corresponds to the highest degree of sustainability, the results of the simulations suggest that even in ideal conditions, such as shown with the combination $W_1 = W_2 = W_3 = 0.33$ with $I_1 = I_2 = I_3 = 1.0$ (Fig. 2a), $IS\lambda_{0.00}$ will never be equal to one. Conversely, in this condition, $IS\lambda_{0.00}$ tends to be closer to zero than one (0.33 in this case), suggesting that the system is unsustainable, which is not a reflection of the input values in this scenario.

On the other hand, IS_S and $IS\lambda_{1.00}$ have a high compensation power. If an attribute or dimension obtains a zero value, it will be masked by another with a higher value. This implies, for example, that any environmental conflict can be solved with economic compensation with IS not reflecting such differences, which is the opposite of the multidimensional and integrated concept of sustainability. Hediger (1999) indicates that assuming total compensation between indicators is associated with the concept of 'weak' sustainability, which implies the possibility of replacing the effect of one indicator by another.

Using intermediate compensation values ($IS\lambda_{0.25}$, $IS\lambda_{0.50}$, and $IS\lambda_{0.75}$) adds subjectivity to the study since it is necessary to define which value is going to be defined and justify that decision adequately. Considering that the objective of this analysis was to reduce the degree of subjectivity inherent in sustainability analyses, no value is recommended for intermediate partial compensation within the multicriteria function as a single sustainability index.

The product of weighted indicators technique (IS_P) uses a compensation rate between indicators that varies depending on the value of the indicators and the weights. Thus, as the value of an attribute or dimension takes extreme values (close to 0 or 1), the same occurs with its compensation capacity. This implies that an I_k that has a high W_k generates a high degree of compensation. However, if I_k is close to zero, indicating that it is outside the allowed threshold, all the dimensions, and therefore the treatment, would be considered unsustainable. This way, IS_P represents better the potential results in real scenarios than IS_S and IS_λ. The aggregation process refers to attributes or dimensions since this process can be applied to both cases.

Experimental results: comparing treatments

The lower yield of OR directly influences the environmental impact, since the LCA uses a kilogram of fresh tomato as a functional unit, i.e., the more input used to produce a kilogram of tomato, the higher the environmental impact will be generated. Despite being the only treatment to which no organic fertilizers were applied, CR excels in the environmental dimension. In this regard, there is a tendency to increase the environmental impact (PE and GWP) as the amount of organic fertilizer applied (chicken manure) increases, in this order: OR > O75:C25 > O50:C50 > O25:C75 > CR. These results are consistent with those reported by Bojacá *et al.* (2014), who found that fertilization is the agricultural activity that generates the highest negative environmental impact (regardless of infrastructure) and, accordingly, chicken manure is the precursor of this result for most of the categories evaluated in their study on the environmental impact of Colombian greenhouse tomato crop. The high N content of chicken manure is associated with high levels of leaching and N emissions (Bergström and Kirchmann, 2010; Hayakawa *et al.*, 2009).

As for the number of wages (JA), the analysis can be done from two points of view: (1) the farmer (owner of the crop) and (2) the employee. For the farmer, a smaller number of wages is more convenient, while for the employees there is a more significant benefit while more wages

https://doi.org/10.1017/S0014479723000145 Published online by Cambridge University Press

require the crop. For this case study, the analysis was made from the farmer perspective, since a higher number of wages implies higher production costs, which can affect the sustainability of the system alone. Based on this, CR is the most economically sustainable treatment because it requires the fewest number of wages. This has to do with the fertilization scheme, since a smaller number of wages is required when only applying chemical fertilizers in preplanting.

The measurement timespan is too short (one production cycle) to appreciate the application of the organic amendment advantages in the soil and the ecosystem. However, it also influences the fact that chicken manure was used to replace a percentage of the amount of chemical fertilizer, i.e., it was used as a fertilizer, not as an amendment. It is noticeable that compared to chemical fertilizers, whose nutrients are immediately available to the plant, chicken manure has a limited fertilizing action.

In this study, thresholds were not associated with the selected environmental indicators, thus the definition of the level of sustainability was based on the comparison between the evaluated treatments. This simple comparison limits the analysis, especially for the environmental dimension. If hypothetically, all treatments have a negative environmental impact, statistically significant variation forces the assignment of differential sustainability levels (weights). In fact, the world legislation and policy on soil quality are poorly defined due to the diffuse definition of soil quality, which is accentuated by the difficulty inherent in the quantification and mapping of its space variability (de Paul Obade and Lal, 2016).

Final considerations about SMAES

In SMAES, many of the variables that feed the indicators come from core research, and the indicators as measures of sustainability on an experimental scale are able to capture the sources of variation or treatments due to the homogeneity and size of the plots. This is contrary to the sustainability studies on a larger geographical scale, which require a large number of observations due to the heterogeneity of the information source (e.g., Dantsis *et al.*, 2010). Government policies have the same influence on all EU under evaluation in SMAES as well as different computational tools allow calculating specific indicators that act as a complement of the measurements in the field (e.g., LCA), and the classic statistical evaluation is no longer a critical parameter for decision making. This serves as a selection criteria to decide which indicators will be included in the sustainability analysis.

Conclusion

This study provides a conceptualization of SMAES, an adaptable and quantifiable methodology for the evaluation of sustainability oriented to soil-associated agricultural experiments. The outputs are interpreted through a sustainability index that assembles the environmental, social, and economic information of the experiment. SMAES could become part of a decision support tool whose use would allow soil researchers to define how sustainable the evaluated treatments in their experiments are, to improve the reliability, and application feasibility of results that would be transferred to the farmers. When only a few variables are studied and the recommendation is based just on technical results, it can generate biases because it is not considering how the recommended treatment would affect each dimension of the sustainability. Thus, as in this study, if only the yield is considered as an indicator to designate the best treatment, all treatments are recommended exception made for the one with organic fertilizers and amendments applied as preplanting fertilization. However, with the use of SMAES, differences among treatments were revealed, indicating that the most sustainable treatment is the one where chemical fertilizers were not mixed with organic fertilizers. It is important to highlight that SMAES is applied to evaluate the results of the experiments without considering possible replications in time and/or space. Each experiment must be analyzed separately. In this specific study and, in accordance with the literature, it is possible that if the management of the treatments is maintained over time, in 10 or 20 years, the fertilization treatments including organo-mineral mixtures could show the highest yields. On the other hand, the chemical treatment could generate a greater negative environmental impact, which probably makes it unsustainable.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0014479723000145

Financial support. This study is made possible by the support of the Ceiba foundation. Program activities are funded by the Colombian royalty's general system for the state of Cundinamarca. The contents are the sole responsibility of the authors and do not necessarily reflect the views of Ceiba or the Colombian government.

Competing interests. None.

References

Adhikari K. and Hartemink A.E. (2016). Linking soils to ecosystem services – a global review. *Geoderma* **262**, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009

Adhikari P., Araya H., Aruna G., Balamatti A., Banerjee S., Baskaran P., Barah B.C., Behera D., Berhe T., Boruah P., Dhar S., Edwards S., Fulford M., Gujja B., Ibrahim H., Kabir H., Kassam A., Khadka R.B., Koma Y.S., Natarajan U.S., Perez R., Sen D., Sharif A., Singh G., Styger E., Thakur A.K., Tiwari A., Uphoff N. and Verma, A. (2018). System of crop intensification for more productive, resource-conserving, climate-resilient, and sustainable agriculture: experience with diverse crops in varying agroecologies. *International Journal of Agricultural Sustainability* **16**, 1–28. https://doi.org/10.1080/14735903.2017.1402504

Afshar R.K. and Dekamin M. (2022). Sustainability assessment of corn production in conventional and conservation tillage systems. *Journal of Cleaner Production* **351**, 131508. https://doi.org/10.1016/j.jclepro.2022.131508

Akinnifesi F., Makumba W. and Kwesiga F. (2006). Sustainable maize production using gliricidia/maize intercropping in southern Malawi. *Experimental Agriculture* **42**, 441–457. https://doi.org/10.1017/S0014479706003814

Alaoui A., Hallama M., Bär R., Panagea I., Bachmann F., Pekrun C., Fleskens L., Kandeler E. and Hessel R. (2022). A new framework to assess sustainability of soil improving cropping systems in Europe. *Land* **11**, 729. https://doi.org/10.3390/land11050729

Antón A. (2004). Utilización del análisis del ciclo de vida en la evaluación del impacto ambiental del cultivo bajo invernadero mediterráneo. Barcelona. Universitat Politècnica de Catalunya. PhD Thesis. http://tdx.cat/handle/10803/6827.

Astier M., Speelman E.N., López-Ridaura S., Masera O.R. and Gonzalez-Esquivel C.E. (2011). Sustainability indicators, alternative strategies, and trade-offs in peasant agroecosystems: analysing 15 case studies from Latin America. *International Journal of Agricultural Sustainability* **9**, 409–422. https://doi.org/10.1080/14735903.2011.583481

Baush J.C., Bojórquez L.T. and Eakin H. (2014). Agro-environmental sustainability assessment using multicriteria decision analysis and system analysis. *Sustainability Science* 1–17. https://doi.org/10.1007/s11625-014-0243-y

Bergström L.F. and Kirchmann H. (2010). Leaching of total nitrogen from nitrogen-15-labeled poultry manure and inorganic nitrogen fertilizer. *Journal of Environmental Quality* **28**, 1283. https://doi.org/10.2134/jeq1999.00472425002800040032x

Binder C.R., Feola G. and Steinberger J.K. (2010). Considering the normative, systemic and procedural dimensions in indicator-based sustainability assessments in agriculture. *Environmental Impact Assessment Review* **30**, 71–81. https://doi.org/10.1016/j.eiar.2009.06.002

Bogotá Trade Chamber (CCB). (2019). Steps to create company. Available at www.ccb.org.co; (accessed 25 June 2019).

Bojacá C.R., Wyckhuys K.A.G. and Schrevens E. (2014). Life cycle assessment of Colombian greenhouse tomato production based on farmer-level survey data. *Journal of Cleaner Production* **69**, 26–33. https://doi.org/10.1016/j.jclepro.2014.01.078

Dantsis T., Douma C., Giourga C., Loumou A. and Polychronaki E.A. (2010). A methodological approach to assess and compare the sustainability level of agricultural plant production systems. *Ecological Indicators* **10**, 256–263. https://doi.org/10.1016/j.ecolind.2009.05.007

De Olde E., Moller H., Marchand F., McDowell R.W., MacLeod C.J., Sautier M., Halloy S., Barber A., Benge J., Bockstaller C., Bokkers E.A.M., De Boer I.J.M., Legun K.A., Le Quellec I., Merfield C., Oudshoorn F.W., Reid J., Shader C., Szymanski E., Sorensen C.A.G., Whitehead J. and Manhire J. (2016). When experts disagree: the need to rethink indicator selection for assessing sustainability of agriculture. *Environment, Development and Sustainability* 1–16. https://doi.org/10.1007/s10668-016-9803-x

De Paul Obade V. and Lal R. (2016). A standardized soil quality index for diverse field conditions. *Science of the Total Environment* **541**, 424–434. https://doi.org/10.1016/j.scitotenv.2015.09.096

Deytieux V., Munier-Jolain N. and Caneill J. (2016). Assessing the sustainability of cropping systems in single- and multi-site studies. A review of methods. *European Journal of Agronomy* **72**, 107–126. https://doi.org/10.1016/j.eja.2015.10.005

Direction of National Taxes and Customs (DIAN) (2019). Tax estatus. Available at www.dian.gov.co (accessed 25 June 2019).

Dong F., Mitchell P.D. and Colquhoun J. (2015). Measuring farm sustainability using data envelope analysis with principal components: the case of Wisconsin cranberry. *Journal of Environmental Management* **147**, 175–183. https://doi.org/10.1016/j.jenvman.2014.08.025

Ecoinvent Centre. (2017). Ecoinvent Data V. 2.0. Version 3.4. Swiss centre for life cycle inventories. Available at http://www.ecoinvent.org.

Freudenberg M. (2003). Composite indicators of country performance: a critical assessment. *OECD Science, Technology Industry Working Paper* **16**, 35. https://doi.org/10.1787/405566708255

Gómez-Limón J.A. and Sanchez-Fernandez G. (2010). Empirical evaluation of agricultural sustainability using composite indicators. *Ecological Economics* **69**, 1062–1075. https://doi.org/10.1016/j.ecolecon.2009.11.027

Gu Y.J., Han C.L., Fan J.W., Shi X.P., Kong M., Shi X.Y., Siddique K.H.M., Zhao Y.Y. and Li F.M. (2018). Alfalfa forage yield, soil water and P availability in response to plastic film mulch and P fertilization in a semiarid environment. *Fields Crops Research* **215**, 94–103. https://doi.org/10.1016/j.fcr.2017.10.010

Guinée J.B., Gorree M., Heijungs R., Huppes G., Kleijn R., De Koning A., Wegener Sleeswijk A., Suh S., Udo de Haes H.A., De Bruijn J.A., Van Duin R. and Huijbregts M.A.J. (2004). *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards*. The Netherlands: Kluwer.

Hayakawa A., Akiyama H., Sudo S. and Yagi K. (2009). N2O and NO emissions from an Andisol field as influenced by pelleted poultry manure. *Soil Biology and Biochemistry* **41**, 521–529. https://doi.org/10.1016/j.soilbio.2008.12.011

Hediger W. (1999). Reconciling 'weak' and 'strong' sustainability. *International Journal of Social Economics* **26**, 1120–1143. https://doi.org/10.1108/03068299910245859

Heijungs R. and Guinée J.B. (2012). An overview of the life cycle assessment method – past, present, and future. In: Curran M. A (ed), *Life Cycle Assessment Handbook. A Guide for Environmentally Sustainable Products*. USA: Willey, pp. 15–42. https://doi.org/10.1002/9781118528372.ch2

Karibskii A.V., Shishorin Y.R. and Yurchenko S.S. (2003a). Financial and economic analysis and efficiency evaluation of investment projects and programs. I. *Automation and Remote Control* **64**, 886–904. https://doi.org/10.1023/a:1024129430374

Karibskii A.V., Shishorin Y.R. and Yurchenko S.S. (2003b). Financial and economic analysis and efficiency evaluation of investment projects and programs. II. *Automation and Remote Control* **64**, 1205–1224. https://doi.org/10.1023/a:1025003529815

Lanfranco B.C. and Helguera L.P. (2006). Óptimo técnico y económico. Diversificación, costos ocultos y los estímulos para mejorar los procreos en la ganadería nacional. *Revista INIA* **8**, 2–5.

Lebacq T., Baret P.V. and Stilmant D. (2013). Sustainability indicators for livestock farming. A review. *Agronomy for Sustainable Development* **33**, 311–327. https://doi.org/10.1007/s13593-012-0121-x

Marchand F., Debruyne L., Triste L., Gerrard C., Padel S. and Lauwers L. (2014). Key characteristics for tool choice in indicator-based sustainability assessment at farm level. *Ecology and Society* **19**, 46–56. https://doi.org/10.5751/ES-06876-190346

Monsalve C.O.I., Bojacá A.C.R. and Henao T.M.C. (2021a). Agricultural sustainability indicators associated with soil properties, processes, and management. *Corpoica Ciencia y Tecnologia Agropecuaria* **22**, e1919. https://doi.org/10.21930/rcta.vol22_num3_art:1919

Monsalve C.O.I., Gutiérrez D.J.S., Bojacá A.C.R., Henao T.M.C. and Espitia M.E.M. (2021b). Soil quality indicators with potential use at plot or experimental unit scale. *Eurasian Soil Science* **54**, 62–75. https://doi.org/10.1134/S1064229321140027

Monsalve C.O.I. and Henao T.M.C. (2022). Selection of the minimum indicator set for agricultural sustainability assessments at the plot scale. *Agronomia Colombiana* **40**. https://doi.org/10.15446/agron.colomb.v40n1.98797

Moore A., Dormody T., VanLeeuwen D. and Harder A. (2014). Agricultural sustainability of small-scale farms in Lacluta, Timor Leste. *International Journal of Agricultural Sustainability* **12**, 130–145. https://doi.org/10.1080/14735903.2013.842341

Munda G. (2005). "Measuring sustainability": a multi-criterion framework. *Environment, Development and Sustainability* **7**, 117–134. https://doi.org/10.1007/s10668-003-4713-0

OECD, Organization for Economic Co-operation and Development — JRC, Joint Research Centre (2008). *Handbook on Constructing Composite Indicators. Methodology and User Guide*, 1st ed. Paris: OECD.

Pretty J., Sutherland W.J., Ashby J., Auburn J., Baulcombe D., Bell M., Bentley J., Bickersteth S., Brown K., Burke J., Campbell H., Chen K., Crowley E., Crute I., Dobbelaere D., Edwards-Jones G., Funes-Monzote F., Godfray H.C.J., Griffon M., Gypmantisiri P., Haddad L., Halavatau S., Herren H., Holderness M., Izac A.M., Jones M., Koohafkan P., Lal R., Lang T., McNeely J., Mueller A., Nisbett N., Noble A., Pingali P., Pinto Y., Rabbinge R., Ravindranath N.H., Rola A., Roling N., Sage C., Settle W., Sha J.M., Shiming L., Simons T., Smith P., Strzepeck K., Swaine H., Terry E., Tomich T.P., Toulmin C., Trigo E., Twomlow S., Vis J.K., Wilson J. and Pilgrim S. (2010). The top 100 questions of importance to the future of global agriculture. *International Journal of Agricultural Sustainability* **8**, 219–236. https://doi.org/10.3763/ijas.2010.0534

Rossi J.P., Franc A. and Rousseau G.X. (2009). Indicating soil quality and the GISQ. *Soil Biology and Biochemistry* **41**, 444–445. https://doi.org/10.1016/j.soilbio.2008.10.004

Starkl M., Brunner N., Das S. and Singh A. (2022). Sustainability assessment for wastewater treatment systems in developing countries. *Water* **14**, 241. https://doi.org/10.3390/w14020241

Tóth G., Hermann T., da Silva M.R. and Montanarella L. (2018). Monitoring soil for sustainable development and land degradation neutrality. *Environmental Monitoring and Assessment* **190**. https://doi.org/10.1007/s10661-017-6415-3

Uphoff N. (2003). Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. *International Journal of Agricultural Sustainability* **1**, 38–50. https://doi.org/10.3763/ijas.2003.0105

Van Asselt E.D., Van Bussel L.G.J., Van der Voet H., Van der Heijden G.W.A.M., Tromp S.O., Rijgersberg H., Van Evert F. and Van Wagenberg C.P.A. (2014). A protocol for evaluating the sustainability of agri-food production systems-A case study on potato production in peri-urban agriculture in The Netherlands. *Ecological Indicators* **43**, 315–321. https://doi.org/10.1016/j.ecolind.2014.02.027

van der Vossen H. (2005). A critical analysis of the agronomic and economic sustainability of organic coffee production. *Experimental Agriculture* **41**, 449–473. https://doi.org/10.1017/S0014479705002863

Wang L., Palta J.A., Chen W., Chen Y. and Deng X. (2018). Nitrogen fertilization improved water-use efficiency of winter wheat through increasing water use during vegetative rather than grain filling. *Agricultural Water Management* **197**, 41–53. https://doi.org/10.1016/j.agwat.2017.11.010

Cite this article: Monsalve Camacho OI, Castillo-Romero OG, Bojacá Aldana CR, and Henao Toro MC. Sustainability assessment methodology oriented to soil-associated agricultural experiments. *Experimental Agriculture*. https://doi.org/10.1017/S0014479723000145