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The LCA4CSA framework: Using Life Cycle Assessment to Strengthen Environmental Sustainability Analysis of Climate Smart Agriculture options at farm and crop system levels

Ivonne Acosta-Alba[1,2,3], Eduardo Chia[3,4], Nadine Andrieu[1,2,3*]

[1] French Agricultural Research Centre for International Development (CIRAD), UMR Innovation, F-34398 Montpellier, France

[2] International Center for Tropical Agriculture (CIAT), Km 17 Recta Cali-Palmira, Apartado Aéreo 6713, Cali, Colombia

[3] Univ Montpellier, Montpellier, France

[4] French National Institute for Agricultural Research, UMR Innovation, Campus Supagro Montpellier2 place Viala 34060 Montpellier Cedex 2, France

***Corresponding Autor:** nadine.andrieu@cirad.fr

Abstract

Climate Smart Agriculture (CSA) seeks to meet three challenges: improve the adaptation capacity of agricultural systems to climate change, reduce the greenhouse gas emissions of these systems, and ensure local and global food security. Many CSA assessment methods that consider these three challenges have emerged, but to better assess the environmental resilience of farming systems, other categories of environmental impacts beyond climate change need to be considered. To meet this need, we propose the LCA4CSA method, which was tested in southern Colombia for family farming systems including coffee, cane and small livestock production. This methodological framework is based on Life Cycle Assessment

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(LCA) and multi-criteria assessment methods. It integrates CSA-related issues through the definition of Principles, Criteria and Indicators, and involves farmers in the assessment of the effects of CSA practices. To reflect the complexity of farming systems, the method proposes a dual level of analysis: the farm and the main cash crop/livestock production system. After creating a typology of the farming systems, the initial situation is compared to the situation after the introduction of a CSA practice. In this case, the practice was the use of compost made from coffee processing residues. The assessment at the crop system level made it possible to quantify the mitigation potential related to the use of compost (between 22 and 41%) by taking into account operations that occur on and upstream of the farm. However, it showed that pollution transfers exist between impact categories, especially between climate change, acidification and terrestrial eutrophication indicators. The assessment made at the farming system level showed that farms with livestock units could further limit their emissions by modifying the feeding of animals due to the large quantities of imported cereals. The mitigation potential of compost was only 3% for these farms. This article demonstrates the merits of using life cycle thinking that can be used to inform stakeholder discussions concerning the implementation of CSA practices and more sustainable agriculture.

Keywords: Environmental Sustainability; Farm; Crop System; Mitigation.

1. Introduction

Today, 32% to 39% of the variability in crop yields around the world is due to the climate and translates into annual production fluctuations of 2 to 22 million tonnes for crops such as maize, rice, wheat and soybeans (Ray et al., 2015). At the same time, agriculture and livestock contribute between 19% and 29% of global greenhouse gas (GHG) emissions (Vermeulen et al., 2012). In addition, FAO anticipates that by 2050, 60% more food will be needed for a world population that is growing and changing its consumption patterns through the consumption of more protein (Alexandratos et Bruinsma 2012). Agriculture thus faces a triple challenge: improving the adaptation capacity of agricultural systems to climate change, reducing their impact on the environment on which they depend, and ensuring local and global food security (FAO 2013).

To meet these three challenges, FAO proposes to mobilize Climate Smart Agriculture (CSA). CSA is presented as a winning strategy in three respects. It targets three objectives, also known as pillars: (1) sustainably increase productivity to support development, an equitable increase in farm incomes and food security, (2) increase resilience (adaptation), and (3) reduce or eliminate GHG (mitigation) (de Nijs et al., 2014a; FAO 2010; Lipper et al., 2014). At the interface between science and public policy making, the concept aims to promote action on the ground and mobilize funding (Saj et al., 2017).

In recent years, many initiatives to render CSA operational have emerged on several spatial scales (country, region, locality) integrating diverse types of innovation (technical, institutional, collective) (Brandt et al., 2017; Neufeldt et al., 2015). They have led to the development of numerous assessment methods to prioritize and implement CSA.

These new methods are based on economic calculations such as cost-benefit analysis (Andrieu et al., 2017a; Bouyer et al., 2014), intermediate calculations of gross margins, costs and earnings (Hammond et al., 2017; Mwongera et al., 2017). They are sometimes associated with environmental assessments such as participatory analysis of natural resource management (NRM status) (Mwongera et al., 2017). Other methods take into account the environment to varying degrees depending on land use, land cover and agro-climatic zones.

Nijs et al. (2014) seek to characterize the effects of changes in climate variables on agricultural systems considering site-specific variables (water, nutrients, crop and geographical characteristics). As with the other methods, the pressure exerted by agricultural systems on natural resources is assessed by indicators of emissions or use of resources (nitrogen, water, carbon, energy, etc.) without estimating the potential impact and fate of the substances on the ecosystems themselves.

Moreover, Saj et al. (2017) show that for CSA initiatives to gain credibility, more explicit definitions are needed of the kind of agriculture capable of providing and preserving the ecosystem services on which the agriculture depends, such as pollination, biological control of pests, and the maintenance of soil structure and fertility (Power, 2010). Therefore, multi-criteria assessment methods of the environmental impact that disrupts the nutrient and hydrological cycles which are providing these services are required.

Life cycle assessment (LCA) is a reference method for the integrated assessment of environmental impacts: from "cradle" to "grave" (Guinee et al., 2002). It is used increasingly to evaluate agricultural and food systems and to analyse the links between environmental issues and food security issues (Hayashi et al., 2005; Notarnicola et al., 2017; Sala et al., 2017). LCA provides and assesses quantitative indicators of potential environmental impacts by taking into account the fate of emissions and linking them to categories of impacts on local, regional and global ecosystems. It is thus a potentially useful approach to strengthen the methods used to evaluate CSA options.

The purpose of this article is to present the methodological framework **LCA4CSA (Life Cycle Assessment for Climate Smart Agriculture)** which enables the assessment of CSA options to be strengthened by integrating life cycle thinking. The article has two parts: the first describes the design and implementation in a pilot site in Colombia of each step of the methodological framework, the second discusses the advantages of the framework in assessing CSA.

2. The 5 steps of LCA4CSA

LCA is an assessment method standardized by ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b). It involves successive steps: the definition of the system and the objectives, the inventory of the life cycle, the evaluation of the impacts on the environment, and a transversal phase of interpretation and the proposal of paths for improvement. When LCA is used to assess sustainability, the stages of inventory analysis and impact assessment often are not very differentiated (Guinée, 2016). Recently, LCA has also been used in participatory research and multicriteria analysis of sustainability (De Luca et al., 2017), which seems appropriate for the co-design approaches that interest us.

We have broken down LCA4CSA into 5 steps (Figure 1), drawing from methods used to assess environmental sustainability in agriculture, to take into account the various environmental issues associated with CSA. In these environmental sustainability assessment methods, the steps do not follow one another in a linear fashion. Permanent interactions exist between the steps, and the assessment cycle is continually repeated to gradually move towards the desired goal. We will describe each step by specifying how we propose to implement each of them to assess the effects of adopting CSA practices.

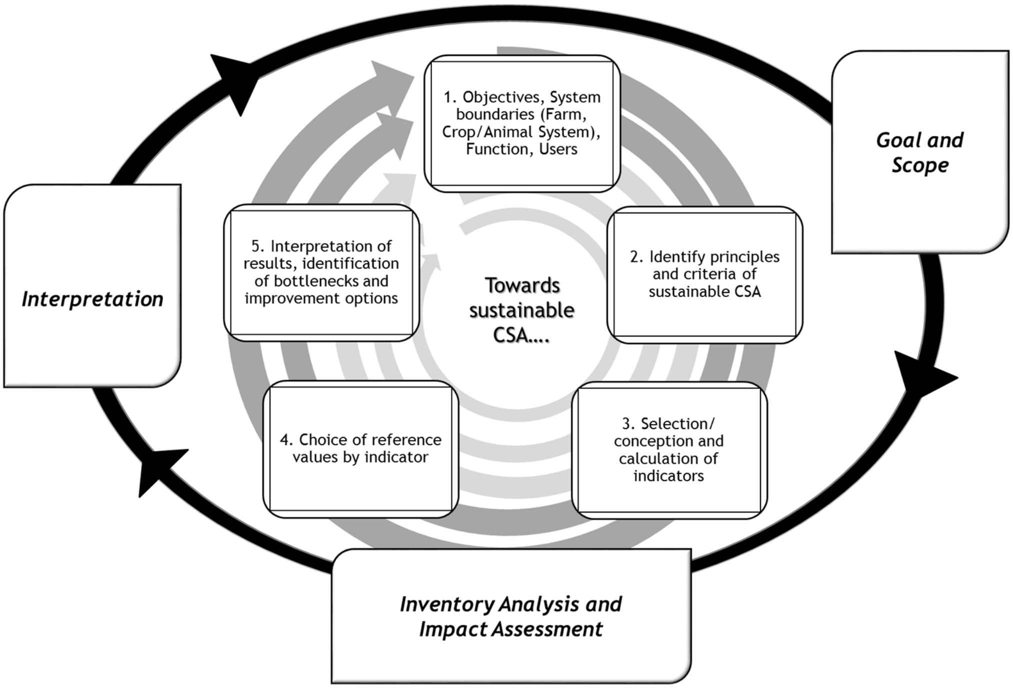

Figure 1. Steps of the LCA4CSA and their link to the conventional steps of LCA

2.1. Step 1. Definition and delimitation of the assessment

2.1.1. Methodological approach of step 1

In step 1, the elements that will structure the analysis are described (the objectives of the assessment, as well as the intended audience, the contours and the function of the system). The main objective of

LCA4CSA is to help stakeholders choose the best CSA options by considering not only climate change but also other environmental issues. Scenarios with and without CSA options are evaluated to inform discussions and decision-making. The contours of the system to be assessed, as well as the temporal and spatial scales of the analysis, are established by a rapid description of the site (soil type, climate and precipitation). Details on the type of production system and/or sector and the segments of the value chain to be included (processing, distribution, consumption, disposal and recycling, etc.) are also established. A clear diagram helps to illustrate which components of the system are to be considered in the analysis.

In this step, the function(s) of the systems to be assessed are described. In LCA, environmental impacts are associated with a functional unit, which is the main function of the system expressed in a quantitative manner. In agriculture, the functional unit often corresponds to the products sold (Weiler et al., 2014). This restricts farming systems to the sole function of supplying products and does not correspond to the reality of many family farms which rely on their diversity and multi-functionality. In addition, prioritizing functions is difficult and carries the risk of omitting some.

In LCA4CSA, we propose to identify and choose the function of the agricultural systems with farmers and local stakeholders. The functional unit to be used stem from this choice. Even two or three functional units can be used. We also recommend using two levels of analysis:

- the crop system or the livestock production system with a functional unit that considers the surface area and temporality,
- the whole farming system analysed to include all of the farm’s productions.

The crop or livestock production system level enables one to consider more technical or production-specific aspects in greater depth. Home-consumed products must always be considered. In the case of perennial cash crops, this level thus makes it possible to consider the productive and non-productive years of the production cycle as well as the associated crops that may exist. The functional unit can be the production per cultivated area. For cases where the systems to be analysed involve livestock production, functional units per head or per forage area unit may be used. Haas et al. (2000) point out that mass units should be avoided when there are several products and a clear allocation cannot be achieved. The functional unit(s) refer to the function of the system but also to the performance and to a temporal dimension. Nemecek et al. (2011a) studied land management, financial and economic functions having three different functional units. In LCA4CSA at least the potential impact of GHG emissions should be related to different functions. Nemecek et al., (2011b) remind the importance of considering the whole farm context when analyzing environmental issues of innovative low-input strategies to be adopted in farm systems

To consider the diversity of farm operating strategies, we recommend developing a typology. This enables a more refined comparative analysis and facilitates the formulation of a differentiated diagnosis (Perrot, 1990; Lopez-Ridaura et al., 2018). In regions where farming systems are well documented and referenced, the typology can be based on expert opinion. When such is not the case, statistical methods can be used to identify farm types with common characteristics (Mądry et al., 2013). Variables such as investment capacity, available workforce, number of family members, and age can be taken into account in order to propose recommendations that can be adapted to farmers' actual reality and their own life cycles (Feintrenie et al., 2013).

2.1.2. Implementation of step 1

The method was applied as part of a participatory research exercise conducted with farmers, representatives of local communities, an NGO and researchers in a village in a rural area of Popayan in Cauca Valley (76 ° 40 '58.1092' W 2 ° 31 '35.5288 "N) in Colombia.

The soils of the area are sandy clay, sandy loam and loam with organic matter levels between 1.3 and 11.57 units. Soils are rather acidic (pH 3.71 to 4.9). The average precipitation between 2011 and 2016 was 2460 mm. Agriculture is the main activity. The main crops are coffee and sugar cane to make *panela*, a solid product similar to unrefined sugar. These two crops are among the three leading crops in the country, accounting respectively for 30% and 11% of surface areas (DANE 2016). In the region, three cropping systems exist for coffee cultivation: shade-free coffee, coffee with a transition crop for non-productive years, and coffee with permanent shade (Arcila et al., 2007). Coffee has a 7-year cycle after which it is cut down to the stump. The coffee plant remains on the plot for 2 to 3 cycles before being replanted. There are two manual harvests per year. Sugar cane remains in place over 10 years and is harvested at maturity every 18 months. Despite the long-term nature of the main cash crops, the balance between coffee and sugar cane can change according to product prices and household needs. The sugar cane crop, which had been neglected in recent years, has been revived with rising prices and demand. For animals, short-cycle species (poultry and pigs) are sold several times a year, every 50 days and 120 days respectively. They are given purchased feed. Cattle are cross-bred local breeds raised especially for meat. They spend half the time in pasture and are supplemented with feed based on corn and soybeans.

The research aimed to co-identify and test technical options to enhance farmers' ability to cope with climate change. The specific objective was to propose a method that could be used by technical and scientific actors to assess the effects of supposed "climate smart" practices.

One of the technical options identified and prioritized by stakeholders in the region was compost. These stakeholders hypothesized that using compost as a substitute for mineral fertilizers could make it possible to limit greenhouse gas emissions, and durably improve productivity and adaptation via a more efficient use of mineral resources (Schaller et al., 2017). Compost produced on the farm consisted of 80% fermented coffee pulp (nitrogen content 4.2%) and 20% poultry manure (nitrogen content 8%). When there was no livestock unit on the farm, the manure needed was purchased locally. Compost was made manually, without the use of either energy or any specific material.

The function attributed to farms by farmers in exploratory surveys, and validated at a workshop involving 48 farmers, was income generation through the production of quality coffee. They wanted to maintain the region’s coffee tradition and focus on quality with the possibility of creating a “CSA coffee” brand. For the other actors (scientists, NGOs), these farms had also to address food security challenges.

The functional unit considered was the ha*year^{-1} unit area. This unit made it possible to consider the productive and unproductive stages of perennial crops as well as transition crops. The temporal scale included the whole crop cycle for perennial crops and the average time of presence in the farm for livestock. The technology used is representative of average practices in smallholder coffee growers in the region.

We decided to compare two scenarios: a reference situation, or "baseline scenario” compared with a scenario with compost produced on site and applied to the coffee crop. In this scenario, the farmers decided to replace 2/3 of purchased mineral nitrogen fertilizers by compost produced on farm. There was equivalence in terms of the nitrogen for the crops.

Two levels of analysis were considered: the coffee crop system, which was the main crop on these farms, and the whole farm, in order to put into perspective, the technical solutions prioritized by the farmers within the production system.

In order to represent the diversity of the farms, an initial farm typology was conducted using statistical analysis methods (Principal Component Analysis followed by Hierarchical Classification) and by mobilizing a database of 170 farms in the study area [dataset[1]]. The natures of the coffee crop (shading, no shading, banana) and livestock systems were used as active variables, while the age of the farm head, family size and plot distribution were additional variables.

The initial analysis led to two very disproportionate groups: 161 and 15 farms. These 15 farms were characterized by a larger area (between 4 and 40 hectares) than the average (1.3 ha) of the 170 farms or a large number of animals (more than 30 heads). They thus constituted a separate farm type (Crops and Husbandries – C&H). For the remaining 161 farms, a second hierarchical cluster analysis (HCA) was

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[1] The survey questionnaire and data are available at the following website: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/28324

conducted which identified four additional types: Coffee Banana (CB), Coffee Banana Transition (CBT), Diversified Crops (DC), and Diversified Crops and Poultry (C & P) (Table 1).

Table 1. Main characteristics of the different types of farms

Variable	Unit	1 CB Coffee Banana	2 CT Coffee Transition	3 DC Diversified Crops	4 C&P Crops and Poultry	5 C&H Crops and Husbandries
Total Area	ha	1.40	1.25	1.60	2.50	40
Agricultural Area	ha	0.5	0.7	1.1	2	20
Sugarcane	ha	-	-	0.33	0.30	2
Coffee	ha	0.5	0.7	0.77	1.7	3
Coffee shaded banana	%	100	70	50	47	
Coffee Inga shaded	%			50	53	100
Coffee non shade	%		30			
N from fertilizers applied on coffee	$Kg*ha^{-1}$	306	312	495	255	153
Family members	persons	2	4	3	4	2
Age of head of family	years	65	33	54	42	66
Yield (green bean coffee)	$ton*ha^{-1}*an^{-1}$	1.54	1.20	0.86	1.29	1.71
Price of sold parchment coffee	$USD*ton^{-1}$	1624	1600	2124	1784	2050
Panela production	$ton*ha^{-1}*an^{-1}$	-	-	1.36	2.22	1.79
Poultry	heads	-	-	-	17	30
Pigs	heads	-	-	-	-	10
Bovines	heads	-	-	-	-	47
Soil characteristics						
Clay	%	40	6	2	6	6
MO	%	1.30	5.18	11.57	5.80	8.22
pH		4.90	4.33	3.71	4.33	3.98

All of the processes, from raw material extraction (cradle) up to the farm gate, were considered. Included in the analysis were coffee and its associated crops and, at the farm level, cane *panela* and livestock production systems when appropriate. The non-productive periods (the first year for coffee and the first 14 months for cane) were considered for the calculation of average yields. The processing steps from coffee cherries to green beans that take place on the farm were also included. Figure 2 summarizes the processes taken into account, including the additional processes associated with the introduction of coffee residue compost, and the two levels of analysis (coffee crop system and farm).

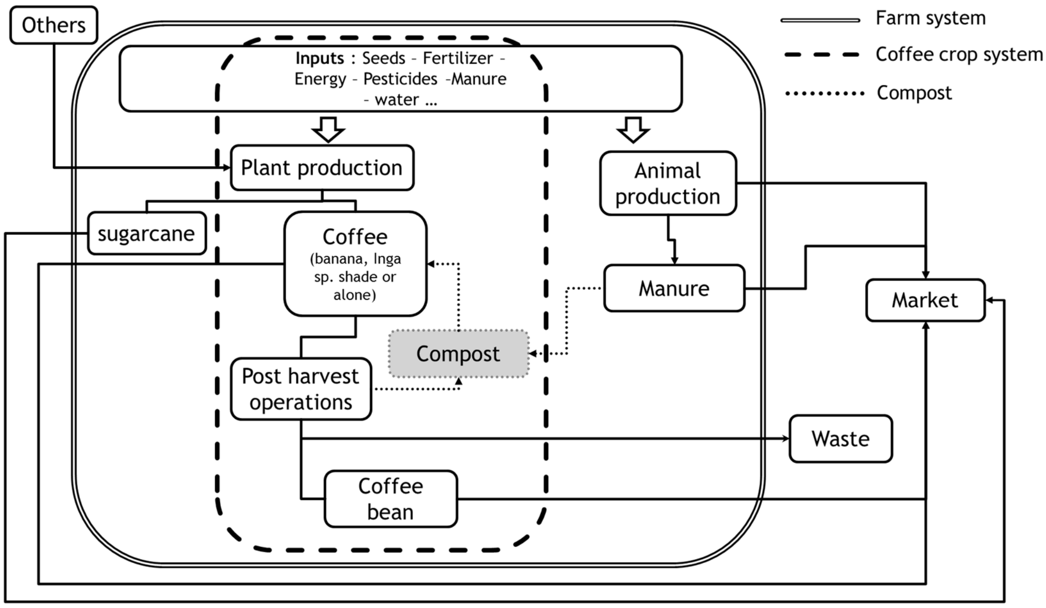


Figure 2. Schematic representation of the system under consideration: at farm and crop system levels

2.2. Step 2 Selection of CSA Principles and Criteria

The second step consists of identifying the principles, the assessment criteria and the associated indicators to be used for each (Rey-Valette et al., 2010). In the LCA4CSA method, these principles are the values promoted by CSA, namely the productivity, adaptation, and mitigation pillars (FA0, 2013). To define the criteria, we used the CSA framework (FAO, 2013) and the existing methods for evaluating CSA initiatives (Appendix A1).

In LCA4CSA, as in LCA, *productivity* is generally associated with measuring the capacity of production factors to generate an output (Latruffe et al., 2018). It is considered through yields and the production of consumable calories. We propose to add socio-economic and food security dimensions that are more atypical in LCA works and which we translate using four criteria: improve household revenue, reduce costs, increase food availability and promote employment (Andrieu et al., 2017a; Hammond et al., 2017).

The criteria of the second principle, *adaptation*, are more heterogeneous in CSA literature (de Nijs et al., 2014). This principle is often associated with resilience, as well as effectiveness of input use and equity. Antwi et al. (2014) propose to measure environmental resilience by the magnitude, the severity and the frequency of disturbances. For Rahn et al. (2014), one of the criteria that reflect the adaptive capacity of agricultural production systems is pollution given its negative effect on the ecosystem and human health.

Adaptation/environmental resilience is therefore defined as the ability of the agrosystem to both recover from disturbances and contribute to the maintenance and sustainability of the natural environment by limiting its impact. In other words, one may refer to the criteria of environmental sustainability, where "the recycling of polluting emissions and the use of resources can be supported in the long term by the natural environment" (Payraudeau and van der Werf, 2005) considering impacts on the local, regional and global environment.

With regard to the mitigation pillar, it is related to a reduction in the intensity of GHG emissions in most methods applied to CSA. One of the criteria established by FAO (2013) that does not clearly appear in recent studies is that of removing GHGs from the atmosphere and enhancing carbon sinks. GHG reduction criteria are established per unit of production (kg, calorie, fuel or fiber), accompanied by non-deforestation by agriculture in the broad sense (crops, livestock and fisheries). In LCA4CSA, mitigation aims to reduce GHG emissions that contribute to the impact of climate change (CC). This reduction is expected overall, by area, product and consumable calories.

The principles and criteria are summarized in Figure 3.

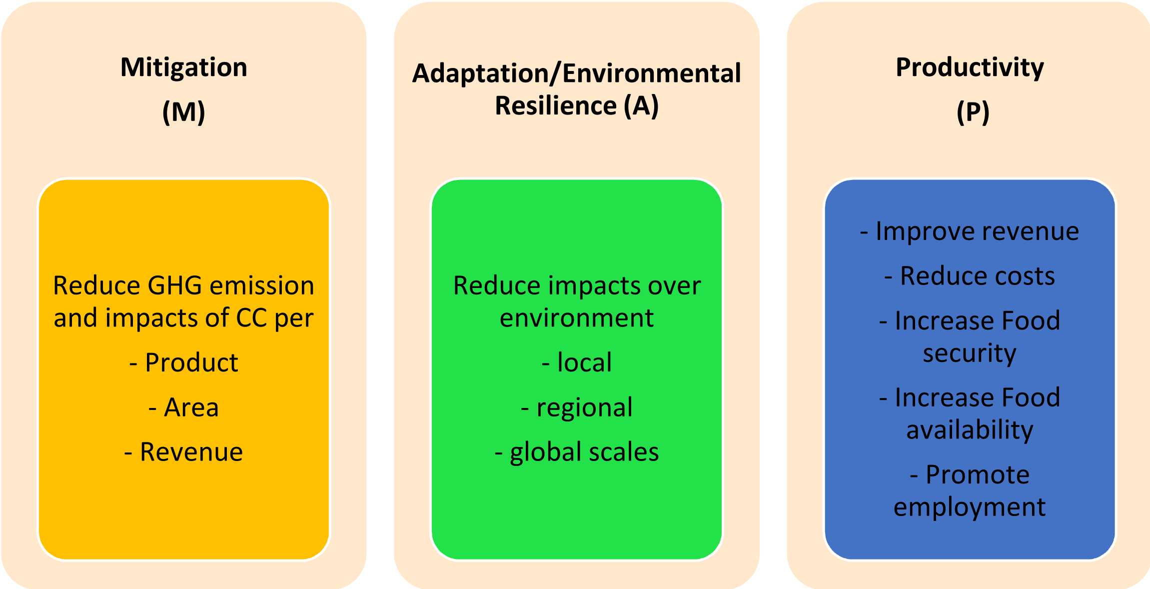


Figure 3. Principles, criteria, and indicators selected for the assessment of CSA options

2.3. Step 3 Selection, Design and Calculation of Indicators

2.3.1. Methodological approach of step 3

This step begins with an *inventory* that is as accurate as possible of the following: all production, transportation, and processing processes; emissions to air, surface water, groundwater and agricultural soils; and resource consumption, whether on the farm or downstream. All operations and agricultural products used are listed (quantity used, provenance and composition). When they exist, machines, buildings and tools are included. The hours and the number of times used per year, including energy consumption (electricity, gas, oil, heat, etc.) as well as the number of paid workers and hours of work are considered.

The indicators to be used are then selected for each criterion.

For productivity, and to assess the criterion "improve household revenue", we propose to consider the costs of production and the benefits generated for different crops and types of animals in US dollars. To estimate the criterion "reduce costs", we propose to consider the costs of inputs such as mineral fertilizers, pesticides, lime, manure and animal feed converted to US dollars. To estimate the criterion “increase food availability”, the proposition is to consider the production of consumable kilocalories from all animal and crop products from farms (sold and home-consumed). To estimate the criterion “promote employment“ the number of paid workers (days of external salaried work) can be considered.

In the case of adaptation/environmental resilience, LCA presents indicators in existing methods that can be used to justify the selection (JRC 2010). First, pollutant emissions to air, surface water, groundwater and agricultural soils are calculated using models for each emission. They are then related to the impact categories by the impact models. International methodological guides include recommendations and models (Food SCP RT 2013; JRC 2010; Koch and Salou, 2016; Nemecek et al., 2014). We suggest to follow the ILCD guidelines which is the international reference Life Cycle Data System published by the Joint Research Centre Institute for Environment and Sustainability of the European Commission (JRC, 2010). Although all models to calculate emissions and indicators are not yet well adapted to tropical contexts, in order to compare different options, assessments can be carried out using impact models developed for the European context (Basset-Mens et al., 2010; Bessou et al., 2013, Castanheira et al., 2017). These guidelines recommend to use eleven potential impact categories : Climate change (global warming potential), (stratospheric) Ozone depletion, Human toxicity, Respiratory inorganics, Ionizing radiation, (ground-level) Photochemical ozone formation, Acidification (land and water), Eutrophication (land and water), Ecotoxicity, Land use, Non-renewable resource depletion (minerals, fossil and renewable energy resources, water). There are all called in LCA, mid-point impact categories in comparison to end-point categories that are mainly damage indicators (human health, resource depletion, and ecosystem quality). We consider that mid-point categories (e.g. Global warming potential) are easier to discuss with farmers to link practices with GHG emissions. The problem oriented mid-point approach allows a better accounting of potential impact than damage level (Thevenot et al., 2013).

Although these eleven impact categories used as indicators are prescribed ex-ante, we recommend reducing the list of indicators in a participatory manner with the farmers during a workshop, considering the issues that, in addition to climate change, are of greatest concern to them. In this case, we recommend keeping at least one impact by environmental "compartment" (air, water, biota, sediments) (Fränzle et al., 2012) and that practitioners carry out an exploratory simulation (called screen analysis in LCA) of the main impact categories in agriculture: global warming, depletion of the ozone layer, acidification, eutrophication, toxicity, land use, water use, energy consumption, particles and biodiversity (Notarnicola et al., 2017). The goal is to ensure that the most significant impacts and those where pollution transfers exist are discussed with the farmers, especially those which were not identified in the workshop.

For mitigation, GHG emissions are taken into account in LCA through the indicator called climate change expressed in CO_2 equivalent and the radiation power of each gas (CO_2, CH_4 and N_2O). Climate Change Potential is obtained by calculating the radiative forcing over a time horizon of 100 years (IPCC, 2006).

2.3.2. Implementation of step 3

Two visits were made in December 2016 and April 2017 to 13 farms implementing compost to establish the technical itinerary of crops. Then, we decide to assess 5 representative farms from a technical point of view, following the typology defined before (see section 2.1.2.) to acquire in-depth data on crop and livestock systems: crop management sequence (for 7 years in the case of coffee), practices (fertilization and pest management practices), amount and type of inputs, costs, soil analyses, among others. We used the data from the farm most typical of each farm type rather than using an average of the data of all of the farms in each type. We chose this approach to conserve the coherence of the farmers' decision-making (see Appendix A2 for details of the characteristics of the farms selected).

For the productivity pillar, we used the mean annual green bean coffee production (including non-productive and productive years of the entire cycle). The conversion factor from coffee cherry to green bean coffee came from Colombian references (Montilla-Pérez et al., 2013). For the calculation of coffee benefits, the exchange rate used to express the economic indicators in US dollars was US$1 = 3,202 Columbian pesos (2017). For the total kilocalories, the Colombian nutritional values tables were used (ICBF, 2015). For the paid workers in this area, only the coffee harvest requires outside labour. For the compost scenarios, given the difficulty of predicting the effect of compost on coffee yield and quality (on which the price depends), only the variation in cost was estimated. The latter included the price difference of the mineral inputs replaced and the price of the manure used for the composting of coffee residues after the pulping process.

For the adaptation pillar, the inventory of the fertilizers, compost, soil acidity correctives, pesticides, insecticides, energy, diesel (weeding, cutting coffee and post-harvest), electricity and water used was established. The emissions from fabrication and transport (background processes in LCA) were selected from the Ecoinvent database v.3.2 (Wernet et al., 2016). The emissions from the use and application of inputs (foreground processes) were calculated using emissions models listed below, all recommended in the World Food LCA Database - WFLDB (Nemecek et al., 2014):

- Emissions to Air: Ammonia due to fertilization is estimated using EMEP/CORINAIR (EEA 2013) Tier2. Dinitrogen monoxide due to fertilization is estimated-with IPCC (2006) Tier 1. Dinitrogen monoxide from indirect from volatilisation and leaching is estimated according to (IPCC, 2006) Tiers 1. Nitrogen oxides due to fertilization are estimated according to EMEP/EEA(2013) Tier2. Carbon dioxide fossil from lime use is estimated with IPCC - (IPCC, 2006) Tiers 1.
- Emissions to groundwater water: Phosphate from leaching using Prasuhn (2006) and Nitrates leached are estimated with SQCB model from Nemecek et al., (2014).
- Emissions to Surface water: Include phosphates from erosion and phosphorus leached calculated according to Prasuhn (2006).

  Emissions to soil: Pesticide emissions (Chlopyrifos) are estimated using Nemecek and Schnetzer (2011) model; Cadmium, copper, zinc, lead, nickel, chromium, mercury were calculated from Freiermuth (2006) and Prasuhn (2006).

To prioritize the adaptation/environmental resilience indicators, exploratory simulations were conducted and a participatory workshop with 45 farmers from the area was conducted to determine the environmental impacts that seemed most problematic and to validate the preliminary outputs with them. A list of the main problems caused by agricultural activities was also proposed by illustrating each problem with images, and this for each natural compartment: water, air, soil, non-renewable resource depletion. The farmers also could propose impacts that had not been listed. Each farmer had the opportunity to choose three impacts/concerns. Each was then asked to position coloured stickers on the three impacts that he/she considered to be most important. Five of the eleven possible environmental impact categories in LCA were prioritized by more than 30% of farmers, in addition to GHG emissions. The impact categories that corresponded to the environmental concerns of farmers were: global warming, depletion of non-renewable resources, aquatic toxicity, fine particle emissions, acidification, water depletion and use. 45% of farmers considered that the non-recycling of plastics could have consequences on the use of energy and non-renewable resources, terrestrial and aquatic toxicity as well as emissions when plastics were burned. 38% of farmers rated excessive water use and water quality problems equally. And lastly 31% considered the impact on soil quality and water scarcity as the main environmental problems.

After a LCA screen analysis (a rapid LCA study for all the eleven impact categories), two other categories were retained because they present important changes according to the scenario considered: terrestrial and aquatic eutrophication. These two impacts generally are used in analyses of the agricultural sector (Koch and Salou, 2016).

Once the indicators had been chosen, the calculations of impacts were made. We used the models and assessment methods recommended in the ILCD2011 report (JRC 2012). The indicators were calculated as follows:

- *Non-renewable resource depletion:* The abiotic resource depletion is considered as "the decrease of availability of functions of resources, both in the environment and economy". It was calculated by LCDI method called Mineral, fossil & renewable resource depletion. Characterization factors are based on extraction rates and reserves for more than 15 types of ore resources grouped in 4 groups, one of those include fossil fuels (van Oers et al., 2002).
- *Freshwater Eco toxicity*: This category was estimated by the model UseTox (Rosenbaum et al., 2008). "USEtox is a multi-compartment environmental modelling tool that was developed to

compare, via LCA, the impacts of chemical substances on ecosystems and on human health via the environment" (ECETOC 2016).

- *Particulate matter*: It considers the intake fraction for fine particles and quantifies "the impact of premature death or disability that particulates/respiratory inorganics have on the population (JRC, 2010).
- *Acidification and Terrestrial eutrophication:* We used the method of Accumulated Exceedance (AE) (Seppälä et al., 2006). "The atmospheric transport and deposition model to land area and major lakes\rivers is determined using the EMEP model combined with a European critical load database" (JRC 2012).
- *Freshwater eutrophication*: It is the expression of the degree to which the emitted nutrients reaches the freshwater end compartment (phosphorus considered as limiting factor in freshwater). It is the averaged characterization factors from country dependent characterization factors (ReCiPe 2009).
- *Water scarcity:* The indicator was applied to the consumed water volume and assesses consumptive water use only. It is based on the ration between withdrawal and availability and modelled using a logistic function (S-curve) in order to fit the resulting indicator to values between 0.01 and 1 m^3 deprived/m^3 consumed. The curve is tuned using OECD water stress thresholds, which define moderate and severe water stress as 20% and 40% of withdrawals, respectively. Data for water withdrawals and availability were obtained from the WaterGap model. (Pfister et al., 2009).

For mitigation, we also used the models and assessment methods recommended in the ILCD2011 report (JRC 2012). The climate change potential indicator was expressed per unit area and per unit of product. At the level of the crop, the units of product considered were coffee yield, edible kilocalories produced (including the transition crops sold) and crop sales. At the farm level, the unit of product was expressed in kilocalories.

2.4. Step 4 Reference values

2.4.1. Methodological approach of step 4

The fourth step consists of choosing the reference value to use. It makes it possible to position the results of the assessment and thus to orient the systems (Acosta-Alba et Van der Werf 2011). This step is often missing from both conventional CSA assessments and LCAs. There are two types of reference values, normative and relative references depending on their source and nature (Figure 4).

Normative reference values make it possible to introduce policy orientations such as reducing GHGs over a given time horizon. Relative reference values also make it possible to compare systems close to each other in order to consider differences in performance that may exist.

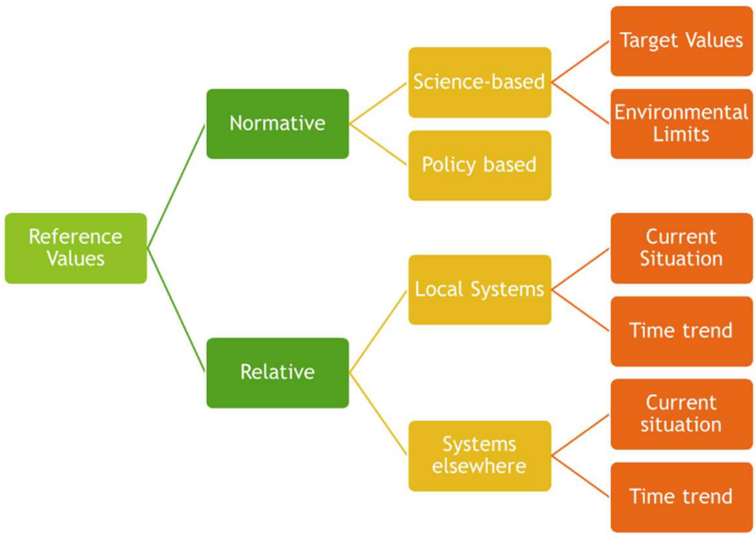


Figure 4. Selection of reference values for the indicators from Acosta-Alba and Van der Werf (2011).

2.4.2. Implementation of step 4

For the pilot application, we chose to use the initial situation before the introduction of compost as the reference value. This was to estimate the relative improvement or deterioration of the indicators with the introduction of compost.

2.5. Step 5 Presentation and Interpretation of Results

2.5.1. Methodological approach of step 5

The interpretation of results makes it possible to diagnose the systems studied and identify the bottlenecks that prevent the achievement of the expected objectives. Possible paths forward are proposed, and once integrated, the assessment cycle can begin again. The crop system/livestock production system level and the farm level will each allow a specific analysis. Another advantage of LCA also can be exploited: the analysis of the direct and indirect contribution of emissions by "item" to better identify sources of emission or "hotspots" and the origin of tensions between indicators.

2.5.2. Implementation of step 5

The results are presented first at the crop system level for the baseline scenario in absolute data (Table 2), and then in terms of relative change by comparing the compost scenarios with the baseline scenarios (Table 3). The same presentation of the results then is used for the analysis at the farm level. The additional absolute values are available in the Appendix A3.

A. Coffee crop system

For baseline scenarios, CO_2 equivalent emissions per hectare and per kilogram of green coffee produced varied from one type of farm to another, ranging from 5.8 t to 8.7 t. These values are close to the values available in the literature and range between 4.5 and 12.5 tonnes of CO_2 equivalent (Ortiz-Gonzalo et al., 2017, Rikxoort et al., 2014).

For farm type 1, the coffee crop system showed relatively low environmental performance for the indicators considered but good performance in terms of productivity. The associated banana production offsetted the lower yields of the export product, enhancing local food security. The coffee crop system of farm type 2 had a similar profile but with lower kilocalorie production and revenues. The coffee crop system of farm type 3 had the poorest performance for the three principles indicators, except the production of kilocalories from banana associated with coffee. For this type, even if part of the performance was explained by soil characteristics (extremely low clay content), better technical management should also be considered because despite very high fertilization (3 times more units than type 5 for example), yields were the lowest.

Coffee crop systems of farm types 4 and 5 performed best in terms of environmental adaptation, unlike their productivity performance, notably when considering the production costs and the production of consumable kilocalories. For example, the higher selling price per ton of green coffee for types 4 and 5 was associated with high production costs without including family labour not taken into account by farmers in their profitability calculations. These farmers seemed to favour the quality of their coffee (a factor that determines the price) and offset these economic losses with other activities.

Table 2. CSA baseline assessment of coffee crop system level per hectare and per year for the different types of farm (reported values include productive and non-productive years and post-harvest stages). The colors series corresponds to the proximity of indicator to criteria: green represents the nearest and red the farthest, orange is intermediate.

Principles	Impact category	Units	1 CB Coffee Banana	2 CT Coffee Transition	3 DC Diversified Crops	4 C&P Crops and Poultry	5 C&H Crops and Husbandries
M	Climate change Potential	kg CO_2eq*ha^{-1}	7785	7730	8759	6884	5844
		kg CO_2eq/t*ha^{-1}	5046	6441	10219	5354	3409
		kg CO_2eq/kcal*10^3*ha^{-1}	2.71	7.91	7.96	7.32	8.30
		kg CO_2eq/$USD*ha^{-1}	2.3	3.2	4.4	2.0	1.3
A	Non-renewable resource depletion	kg Sb eq*ha^{-1}	2.18	2.03	2.41	1.91	1.27
	Freshwater ecotoxicity	CTUe*ha^{-1}	111871	45276	75312	41678	35521
	Water scarcity	m3*ha^{-1}	67.6	64.0	80.9	49.5	39.3
	Freshwater eutrophication	kg P eq*ha^{-1}	3.8	4.0	4.0	3.6	3.0
	Particulate matter	kg PM2.5 eq*ha^{-1}	5.3	5.1	6.4	4.7	4.1
	Acidification	molc H+ eq*ha^{-1}	91.5	92.3	149.2	87.6	73.2
	Terrestrial eutrophication	molc N eq*ha^{-1}	357.7	367.4	623.6	349.3	289.0
P	Coffee production cost	USD$*ha^{-1}	1222.4	1810.5	2332.8	3617.5	3519.8
	Yield (greenbean coffee)	t*ha^{-1}	1.5	1.2	0.9	1.3	1.7
	Total kcalories (coffee and transition crops)	kcal*10^3*ha^{-1}	2876	977	1100	941	704
	Coffee revenue	USD$*t^{-1}	3366	2421	2011	3366	4390
	Paid workers	days*ha^{-1}	77	92	67	76	87

CSA Principles: M: Mitigation; A: Adaptation/Environmental Resilience; P: Productivity

The introduction of compost, made it possible to improve the indicators of the three principles for coffee of type 3. However, they remained below the values obtained for the other farm types. The coffee crop system of farm type 1 showed the weakest improvement in environmental performance for all of the indicators. Farm type 2 improved the environmental performance more significantly. For types 4 and 5, the most notable improvement thanks to the introduction of compost was the reduction of the production costs by more than half.

The introduction of compost allowed an improvement in the mitigation indicator of 22% to 41% for the coffee crop systems of all types of farms. The productivity indicator also was improved by between 30% and 60% thanks to reduced production costs. For all types, compost improved impact categories in relation to water and non-renewable resource depletion but trade-offs appeared with acidification, terrestrial eutrophication and particle emission.

Table 3. Proportional change of indicators values comparing compost scenario to baseline at coffee crop level (%). The colors series corresponds to the improvement (green) and deterioration (red), (orange) when change is limited to 15%

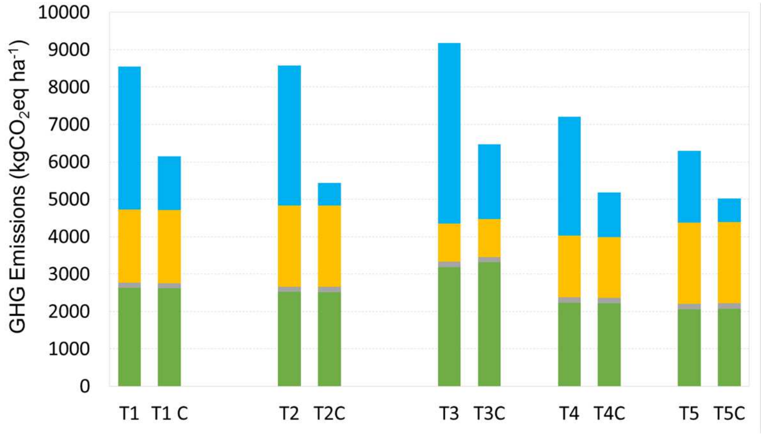
CSA Principles	Indicators	1 CB Coffee Banana	2 CT Coffee Transition	3 DC Diversified Crops	4 C&P Crops and Poultry	5 C&H Crops and Husbandries
M	Climate Change Potential	▼ 29%	▼ 41%	▼ 32%	▼ 30%	▼ 22%
A	Non-renewable resource depletion	▼ 58%	▼ 82%	▼ 58%	▼ 57%	▼ 57%
	Freshwater ecotoxicity	▼ 23%	▼ 54%	▼ 30%	▼ 38%	▼ 30%
	Water scarcity	▼ 61%	▼ 86%	▼ 60%	▼ 53%	▼ 60%
	Freshwater eutrophication	▼ 25%	▼ 27%	▼ 29%	▼ 19%	▼ 10%
	Particulate matter	▲ 18%	▲ 9%	▲ 14%	▲ 12%	0%
	Acidification	▲ 100%	▲ 96%	▲ 74%	▲ 78%	▲ 42%
	Terrestrial eutrophication	▲ 118%	▲ 115%	▲ 83%	▲ 91%	▲ 52%
P	Cost	▼ 39%	▼ 44%	▼ 30%	▼ 60%	▼ 70%

CSA Principles: M: Mitigation; A: Adaptation/Environmental Resilience; P: Productivity

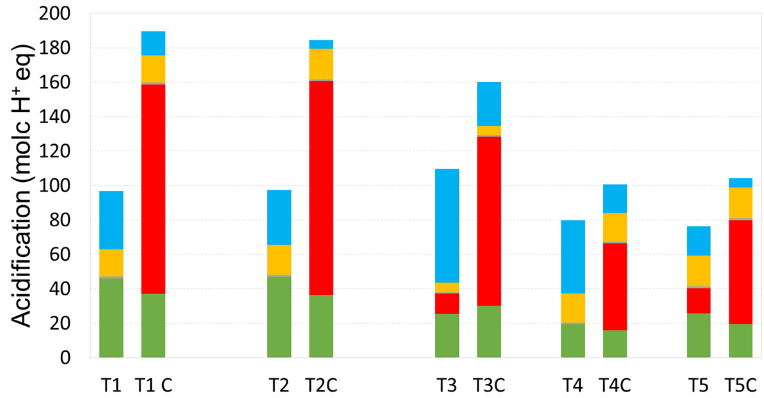
The analysis of the contribution of emissions by item for the indicators in tension (Climate change potential, Acidification and Terrestrial Eutrophication) made it possible to see which part of the coffee production process contributed to the different potential impacts before and after the introduction of compost (Figure 5). GHG emissions that occurred upstream from the farm came mainly from the manufacture of fertilizers and lime used for growing coffee. These represented between 30% and 52% of total emissions and corresponded to orders of magnitude encountered in the literature (Rikxoort et al., 2014). Compost was therefore a favourable alternative in this respect because it rendered it possible to reduce this type of emissions occurring upstream of production, which only accounted for 11% to 22% of total emissions (Figure 5a).

After the introduction of compost, the item on which improvement efforts should focus is energy use, diesel and electricity, because even though electricity in Colombia is hydroelectric, the emissions related to the processing of coffee remained important (Obregon Neira, 2015)

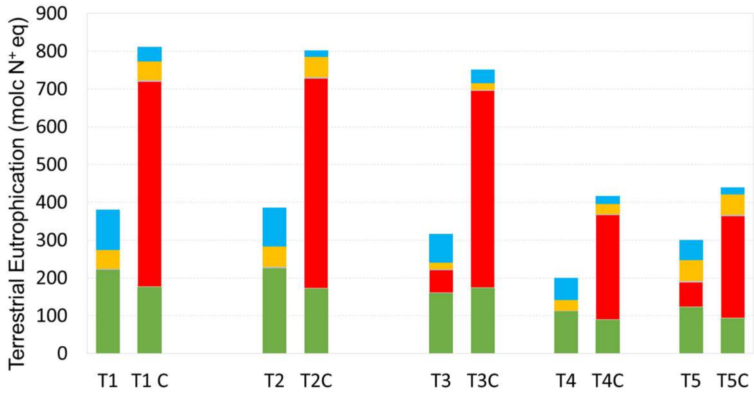
For the acidification (Figure 5b) and terrestrial eutrophication (Figure 5c) indicators, emissions occurred on the farm and were related to fertilizer use. In the second scenario, emissions resulting from compost production were added. Better control of emissions during composting is an interesting way to limit acidification. In addition, to limit terrestrial eutrophication, soil erosion must be limited.



5a. Climate change potential from GHG emissions from main processes of coffee production



5b. Acidification Potential from main processes of coffee production



5c. Terrestrial Eutrophication Potential from main processes of coffee production

On field emissions
Compost fabrication
Mechanical weeding
Transformation (energy)
Off farm

Figure 5. Analysis at the coffee crop system level (productive year), of the main spots of contribution to (a) potential climate change, (b) terrestrial eutrophication and (c) acidification, for the baseline (T) and compost (TC) scenarios and for the 5 types of farms.

B. Farm

The analysis at the farm level enabled a more comprehensive view of the effect induced by compost. Ultimately, it also enabled one to assess whether "the effort is worth it" and if the proposals were in tune with the actual situation of farmers.

In particular, this analysis showed the contribution of other cropping and livestock production systems in generating income, which could explain the poor performance of some of the productivity pillar indicators observed for coffee (Table 4). Type 4 or 5 farmers could thus offset high coffee production costs with income generated by other productions. For type 5, the revenue per farm hectare could seem low, but the utilized agricultural area was much larger (20 ha).

At this level of analysis, the farm types with the best CSA performance were type 3 DC (Diversified Crops) and type 1 CB (Coffee banana); type 4 C & P (Crops and Poultry) had the worst performance (Table 4). For mitigation, the differences between types were much lower at the farm level than at the crop system level, with emissions between 6.3 and 7.7 tonnes of CO_2eq (Table 4). The additional absolute values are available in the Appendix A4.

Table 4. CSA baseline assessment of farms level per hectare and per year. The colors series corresponds to the proximity of indicator to criteria: green represents the nearest and red the farthest, orange is intermediate.

CSA	Impact category	Units	1 CB Coffee Banana	2 CT Coffee Transition	3 DC Diversified Crops	4 C&P Crops and Poultry	5 C&H Crops and Husbandries
Agricultural Area		*ha*	*0.5*	*0.7*	*1.1*	*2*	*20*
M	**Climate Change Potential**	kg CO_2 eq*ha^{-1}	7785	7721	6339	7529	7101
		kg CO_2 eq/kcal*10^3*ha^{-1}	1.35	5.74	2.52	3.98	3.52
A	**Non-renewable resource depletion**	kg Sb eq*ha^{-1}	2.18	2.03	1.71	1.73	0.35
	Freshwater ecotoxicity	CTUe*ha^{-1}	111871	45281	472372	117234	328747
	Water scarcity	m3*ha^{-1}	68	64	57	248	49
	Freshwater eutrophication	kg P eq*ha^{-1}	3.84	4.03	3.76	4.21	1.51
	Particulate matter	kg PM2.5 eq*ha^{-1}	5.32	5.14	4.59	5.57	4.92
	Acidification	molc H+ eq*ha^{-1}	92	92	108	95	171
	Terrestrial eutrophication	molc N eq*ha^{-1}	358	367	450	367	745
P	**Cost**	USD$*ha^{-1}	1841	2480	1983	3702	1070
	Total kcalories	kcal*10^3*ha^{-1}	5752	1344	2517	1890	2016
	Total revenu	USD$*ha^{-1}	3600	2432	2410	3057	1779

CSA Principles: M: Mitigation; A: Adaptation/Environmental Resilience; P: Productivity

The analysis of the introduction of compost at the farm level showed similar trends at the crop system level, such as the improvement of the non-renewable resource depletion indicator (between 22% and 77% depending on the type), the reduction of potential impact on the quantity and quality of water used (respectively between 3% and 97% and 8% to 70% depending on the type) and the unfavourable increase of particles (between 13% and 88%), acidification (72% to 103%) and terrestrial eutrophication (between 81% to 121%). The introduction of compost also made it possible, for all types of farms combined, to reduce GHGs by between 3% and 33% (Table 5), but for Type 5 C & H, the effect was rather limited.

Table 5. Changes in indicator values comparing compost scenario to baseline at farm level (%). The colors series corresponds to the improvement (green) and deterioration (red), (orange) when change is limited to 15%.

CSA	Indicators	1 CB Coffee Banana	2 CT Coffee Transition	3 DC Diversified Crops	4 C&P Crops and Poultry	5 C&H Crops and Husbandries
M	Climate Change Potential	▼ 29%	▼ 33%	▼ 31%	▼ 24%	▼ 3%
A	Non-renewable resource depletion	▼ 55%	▼ 67%	▼ 57%	▼ 22%	▼ 77%
	Freshwater ecotoxicity	▼ 16%	▼ 45%	▼ 3%	▼ 18%	▼ 97%
	Water scarcity	▼ 59%	▼ 70%	▼ 60%	▼ 8%	▼ 56%
	Freshwater eutrophication	▼ 35%	▼ 19%	▼ 22%	▼ 15%	▼ 76%
	Particulate matter	▲ 15%	▲ 17%	▲ 13%	▲ 80%	▲ 88%
	Acidification	▲ 94%	▲ 103%	▲ 72%	▲ 97%	▲ 91%
	Terrestrial eutrophication	▲ 112%	▲ 121%	▲ 81%	▲ 102%	▲ 91%
P	Cost	▼ 26%	▼ 32%	▼ 25%	▼ 50%	▼ 34%

CSA Principles: M : Mitigation; A: Adaptation/Environmental Resilience; P: Productivity

The contribution analysis applied to the mitigation pillar rendered it possible to determine which production subsystems emitted the most and to characterize the improvement brought by the introduction of compost (Figure 6).

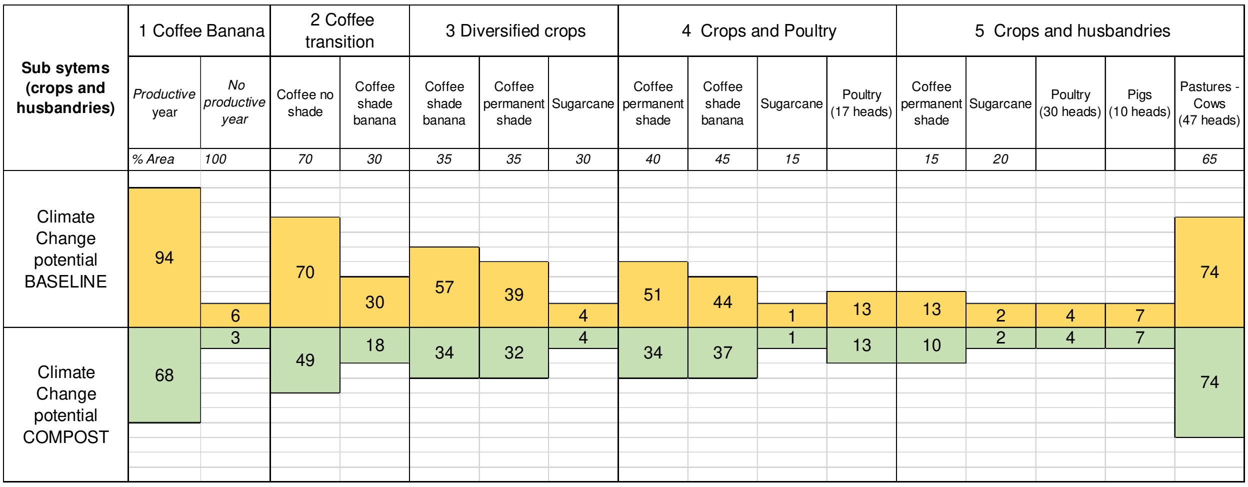


Figure 6. Contribution of the different production sub-systems of the farm to climate change potential (%) before (yellow) and after compost introduction (green).

The contribution of crops in reduction of GHG emissions varied according to the type of coffee crop system present on each type of farm. For farm type 1, and in the case of banana-coffee, the reduction was about 26%, while in types 2, 3 and 4, the estimated reduction was 12%, 23% and 7%. For types 3, 4 and 5, which also had coffee under shade, the reduction of CO_2 emissions following the use of compost was respectively 7%, 17% and 3%.

This contribution analysis applied to mitigation also showed that the practice of compost logically had limited effects on farms where livestock units exist, even in the case of poultry units (17 poultry). For livestock production, the main source of emissions was the concentrated feed purchased. These emissions occur largely in the countries producing raw materials (maize and soybeans) since between 74.5% to 90% of the raw materials used by Colombian concentrate production industries are imported, especially from USA, Bolivia and Brazil (Lopez Borbon, 2016, SIC 2011).

3. Discussion

3.1. LCA useful to strengthen CSA assessment methods

The main challenge for all methods intended to assess the effects of CSA practices is to analyse the trade-offs and synergies between the pillars to respond to debates about the interest and novelty of the CSA approach in the scientific sphere and society in general (Saj et al., 2017; Taylor, 2017; Tittonell, 2015). The results of the LCA4CSA method applied in Colombia demonstrate the added value it offers compared to existing methods. On the one hand, it renders it possible to quantify the effect of introducing a new practice from an environmental and technical-economic point of view. On the other hand, expressing the mitigation pillar not only per kilogram but also per kilocalorie, area and dollars allows one to relate it directly to diverse aspects of productivity (food security, yields, income).

LCA4CSA makes it possible to use the benefits of LCA to assess CSA and thus: (i) the consideration of all production stages from the "cradle" to the "farm gate", and even the "grave"; (ii) the choice of the system's function, which allows one to compare different ways of fulfilling the same function; (iii) highlighting the production stage or process that has the most weight in each impact category; (iv) render visible pollution transfers to avoid solving one environmental problem while creating another (JRC 2010).

In addition, the LCA4CSA method highlighted the difficulty of finding synergies between the different pillars of CSA and between the indicators within the same pillar. Here, we clearly demonstrated the tensions between mitigation and acidification. Even though the search for synergies is most likely futile, it is nevertheless important to assess the effects of the practices promoted on the various dimensions involved to identify ways to minimize tensions. Several authors mention the site-specific nature of CSA (Mwongera et al., 2017; Arslan et al., 2015; Braimoh et al., 2016; de Nijs et al., 2014) where pillars and indicators are prioritized with stakeholders according to the importance given, for example, to adaptation instead of mitigation. The LCA4CSA method can thus be considered in contexts where certain environmental stakes are greater (for example eutrophication of rivers) to prioritize certain environmental indicators.

LCA thus also makes it possible to situate the farm in its local and global environment and to identify which components of the system are to be improved to minimize the impacts on the site and also elsewhere: the production of inputs? their transport? the different farming and livestock systems? the processing? LCA even allows the inclusion of other links in the chain going up to consumption. This is an interesting perspective to be able, as proposed by Taylor (2017), to move beyond the agricultural aspect and include consumption patterns in the search for climate intelligence at the level of the food system as a whole.

Another aspect that remains to be exploited is the consideration of carbon sinks. In LCA, sequestration by soil and plants can be quantified, provided that the timeframe and the effective duration of the sequestration are taken into account. The radiation power of GHGs is calculated for a duration of 100 years. For its part, carbon sequestration is dependent on land use over a period of at least 20 years (Koch and Salou, 2016). Thus, sequestration can be taken into account only when a farm's history is well known and the sequestration sufficiently long.

Better use of LCA in the tropics also involves considering the diversity of farming systems and developing specific methods for the inventory of emissions and the impact assessment of critical issues such as biodiversity. From a methodological perspective, although an incrementing use of LCA in Latin America, the region is still missing specific characterization factors at a local and regional level (Quispe et al., 2017).

3.2. Consideration of farmers' strategies, a challenge for the CSA and LCA communities

In this study, we proposed to strengthen assessment of CSA using LCA. However some lessons can be learned for the LCA community particularly regarding the consideration of different scales of analysis and stakeholder participation.

One of the methodological challenges of this research study lay in the scale of analysis considered and the functional unit chosen for these family farming systems, which fulfil diverse and complementary roles which is complicated to simulate in LCA. Weiler et al. (2014) and Haas et al. (2000) showed that the functional unit and the allocation of impacts to production units reduce the room for manoeuvre and sometimes overestimate the emissions allocated. We see here that for some types of farms, a practice that promotes local animal feed would be more effective than practices focused only on crops.

With the double level of analysis, the LCA4CSA method allows a more nuanced vision of practices such as compost, often presented as a prime example of a CSA practice (Schaller et al., 2017). In our case study, we show that this practice has many advantages, but attention must be paid to ensure its mode of application and to identify the types of farmers for which the practice is most suitable. The farm level was relevant to explore, especially for small farmers whose diversity of crops and herds (cash and home-consumption) have various complementary functions (Herrero et al., 2010).

Other functional units exist, such as monetary units (USD or other currency). This refers to the quality objective by considering the quality of a product by its price (van der Werf and Salou, 2015) when the farmer is the economic agent who receives the profits in an efficient way. This idea is interesting for coffee whose quality can compensate for a decline in income due to lower productivity. The results show a significant difference in the prices paid to the farmer. This can be explained by field practices but also by poorly managed harvesting, fermentation and drying processes as well as product positioning in conventional sectors despite the farmers' desire for high quality.

CSA seeks to guide production systems towards a transformation in which farmers and agricultural stakeholders integrate the reality of climate change into their strategies. Increasingly, CSA research is broadening the framework of subsystem assessments (crop, livestock unit) (Perfecto et al., 2005; Weiler et al., 2014) to take into account all of the farmers' productions and strategies (Hammond et al., 2017; Ortiz-Gonzalo et al., 2017). Transition processes from agricultural systems to CSA need to be developed in a participatory manner. In existing CSA assessment approaches and tools, stakeholders play key roles in prioritizing CSA pillars, indicators and practices (Andrieu et al., 2017b; Mwongera et al., 2017). Few LCA works give such a role to stakeholders. The challenge for the LCA community is to define how to better integrate stakeholders in the various stages of the analysis and make the choice of indicators that are currently mandated more flexible. In our case study, we integrated farmers through workshops that enabled them to prioritize the environmental issues that made sense to them. To do so, we had to translate very technical concepts, such as terrestrial eutrophication and ecotoxicity, into terms corresponding to a concrete reality for them. The existence for several years in this study site of a dynamic integrating NGOs, farmers and researchers in the form of an innovation platform has promoted this type of exchange.

Another challenge is to better define how to make actionable LCA conclusions. Here we have been able to offer the people implementing technical solutions with farmers, ways to improve compost production to avoid the associated impacts in terms of acidification, by better controlling the manufacture of compost to limit ammonia emissions.

Whether in LCA or for the CSA community, promoting an agroecological transition of agricultural systems begins today by considering the complexity of farming systems, but this is not enough. There is a need to go beyond the evaluation of techniques. Although crop diversification and water and soil conservation practices have been proven to contribute to the resilience of traditional agricultural systems in relation to the climate (Altieri et al., 2015), they are not parts that can be simply superimposed without taking into account the entire system. Accompanying farmers in this transition remains a challenge given the urgency of the situation.

4. Conclusion

LCA4CSA seeks to be a tool for thinking about the benefits that technical options can bring to production systems while taking into account the complex dynamics of farming systems. It helps to highlight what is happening on and off the farm, as well as synergies and trade-offs between indicators of a same pillar and even between pillars. Promoting climate-smart agriculture must be accompanied by a multi-criteria environmental assessment to avoid pollution transfers that may go unnoticed when looking at indicators only from a carbon and mitigation perspective. The expression of mitigation by area and product is a way of both reporting the complexity of the systems and proposing more appropriate, relevant and powerful actions to reduce emissions.

The consideration in a participatory way of the multi-functionality of agricultural systems and their multiple environmental impacts are today a necessary point of passage for the development and adoption of agriculture that meets the current challenges, both for researchers and farmers.

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Appendix A1. Principles, Criteria and Indicators of CSA in literature

Method	Objective	Principles (P) et Criteria(C)	Indicator Categories	Results	CSA Options
Climate-Smart Agriculture Colombia profile (World Bank, CIAT, et CATIE 2015):	Initiate discussion using climate scenarios Country profile: snapshot of a developing baseline	P : Productivity, Adaptation, Mitigation C : More efficient, effective and Equitable food systems.	*Climate smartness matrix (Climate, Carbon, Water, Nitrogen smart*; *Energy*; *Knowledge* (altiwal, Zougmoré, et Kinyangi 2013)). Then **Adaptation** (water, yield, stability, resilience), **Mitigation** (C stocks, Energy, Gases Emissions, reduction chemical inputs) and **Productivity** (yield, quality) are estimated.	Score 1 to 5 according to experts panel	Practices maintain or achieve increases in productivity as well as at least adaptation and/or mitigation. Practices were selected according to their Adoption rate, Impact on CSA pillars and Climate smartness effort
Climate-Smart Agriculture Prioritization Framework (CSA-PF) (Andrieu et al. 2017b)	Help decision-makers prioritize their CSA interventions through a process of testing different CSA options and ensures ownership and engagement by key stakeholders	P : Productivity, Adaptation, Mitigation C : Increasing yields, improving resilience, and promoting a low emissions agricultural sector.	**Productivity** (Yield, Variability, Labor, Income) **Adaptation** (Food access, Efficient use of water, Efficient use of fertilizer, Efficient use of other agrochemicals, Use of non-renewable energy, Gendered impact (labor by women) **Mitigation** Emission intensity (Rosenstock et al. 2016)	Score / Cost-Benefit Analysis	Steering committee selected an initial list of 24 relevant practices
Climate smart agriculture rapid appraisal (CSA-RA) (Mwongera et al. 2017)	Identify and prioritize climate smart technologies	P : Food security, Adaptation and Mitigation C: Increase food security and farming system resilience while decreasing greenhouse gas emissions	*Climate Smartness* of practices(Carbon, eau, water, energy, knowledge et climate) ; Social (Gender, Networks), Economic (Assets, Income, Risk), Environmental (NRM status)	Index	Matrix of practices listed by groups (by gender and agroecological zones) and literature (CSA source book, FAO 2013)
The Rural Household Multi-Indicator Survey (RHoMIS) (Hammond et al. 2017a)	Characterize the variability of landscape-scale production systems and strategies to target interventions and promote the emergence of CSA	P : Food security, Adaptive capacity, Mitigation C: support efforts for sustainably using agricultural systems to achieve food and nutrition security, integrating necessary adaptation and capturing potential mitigation.	**Food security**: Food availability, Farm Productivity, Dietary diversity, Food Insecurity of Access **Adaptive Capacity**: Progress out of Poverty, Off Farm Income, Value of Farm Produce, Gender equity **Mitigation**: GHG emissions, GHG intensity	Quantitative indicators, indexes and scores	Agricultural production and market integration (nutrition, food security, poverty and GHG emissions).
Bayesian Belief Network (de Nijs et al. 2014b).	Understanding the impacts of adaptation activities on biophysical vulnerability	P: Resilience C: Building resilience	Assessment of vulnerability to climate change according to land use	Score Vulnerabilit y Index	Intercropping, alley cropping and legume fallows, crop rotation, later maturing cultivars, Water management

	practices, Mulch cover, Low no Tillage.

Appendix A2. Detailed description by type of farm

Variables	1 Coffee Banana	2 Coffee transition	3 Diversified crops	4 Crops and Poultry	5 Diversified crops and Husbandries
Soil type	Sandy clay	Loam	Sand Loamy	Loam	Sandy loam
Spatial distribution of plots	Grouped in 1 block	Grouped in 2 blocks	Grouped in 1 block	Split in 4 blocks	Split
Total Area (ha)	1.4	1.3	1.6	2.5	40.0
Agricultural Area (ha)	0.5	0.7	1.1	2.0	20.0
Family members	3	4	5	4	2
Coffee					
% coffee area	100% CSR	70%CSS; 30%CSR	40% CS; 30% CSR	35% CS; 35% CSR	10% CS
trees/ha	5000	5000	5000	5000	5000
Yield banana (ton)	2.5		0.8	0.5	50.0
Banana trees density/ha	150	30	50	30	
Inga tres density/ha			50	50	
Parchment coffee yield (ton/ha/yr)	1.54	1.2	0.85	1.28	1.7
Mean income of coffee (USD$/ha)	3131	2398	2275	2867	4389
Sugar canne					
Area (ha)			0,3	0,3	3,3
Yield final product ton/ha		0.0	0.0	0.0	0.0
Labor coffee harvest					
Paid workers (days)	45	75	60	150	306

Appendix A3. Replacing 2 mineral nitrogen fertilizers by compost. Indicators quantified by hectare coffee crop system

Principle	Impact category	Units	1 Coffee Banana	2 Coffee transition	3 Diversified crops	4 Crops and Poultry	5 Diversified crops and Husbandries
Mitigation	Climate change	kg CO_2 eq	5495	5019	5997	4794	4579
Adaptation / Environmental Resiliance	Mineral, fossil & ren resource depletion	kg Sb eq	1	1	1	1	1
	Freshwater ecotoxicity	CTUe	93688	23777	52893	25681	24747
	Particulate matter	kg PM2.5 eq	6	6	7	5	4
	Water Scarcity	m3	28	16	32	23	16
	Acidification	molc H+ eq	177	185	259	156	104
	Terrestrial eutrophication	molc N eq	760	807	1144	669	439
	Freshwater eutrophication	kg P eq	2	3	3	3	3
Productivity	Yield (greenbeen coffee)	t	1.5	1.2	0.9	1.3	1.7
	Total kcalories	kcal*10^3	2876	977	1100	941	704
	Total revenu	USD$	3366	2422	2314	2891	4390
	Cost	USD$	743	1009	1631	1446	1067

	Paid workers - harvest	days	77	92	67	76	87

Appendix A4. Replacing 2/3 of mineral nitrogen fertilizers with compost at the farm level. Indicators quantified by hectare of total agricultural area.

Principle	Impact category	Units	1 Coffee Banana	2 Coffee transition	3 Diversified crops	4 Crops and Poultry	5 Diversified crops
Mitigation	Climate Change Potential	kg CO_2 eq	5495	5193	4405	5753	6912
		kg CO_2 eq/kcal*103	1.0	3.9	1.8	3.0	3.4
Adaptation / Environmental Resiliance	Mineral, fossil & ren resource depletion	kg Sb eq	0.97	0.67	0.74	1.34	0.08
	Freshwater ecotoxicity	CTUe	93688	24992	456679	138506	10364
	Particulate matter	kg PM2.5 eq	6.12	6.02	5.20	10.03	0.61
	Acidification	molc H+ eq	177	187	185	187	15
	Water scarcity	m3	27.93	19.21	23.23	228.68	21.67
	Terrestrial eutrophication	molc N eq	760	813	814	742	64
	Freshwater eutrophication	kg P eq	2.5	3.3	3.0	4.8	0.4
Productivity	Cost	USD$	1361	1678	1491	1857	702
	Total kcalories	kcal*103	5752	1344	2517	1890	2016
	Total revenu	USD$	3600	2432	2197	3461	1779

As a reminder, type 1 has a UAA of 0.5ha, type 2 of 0.7ha, type 3. 1.1ha, type 4. 2ha and type 5. 20 ha (including 15 of natural meadows with 47 cattle grazing).