Comparison of Environmental Assessment Methods in the Analysis of the Energy Efficiency in Agricultural Production Systems

MÉNDEZ, C. [a*], RENGIFO, C. F. [b], CORRALES, J. C.[c], FIGUEROA, A.[d]

a. PhD student in Environmental Sciences, University of Cauca, Colombia

b. Professor, Department of Electronics, Instrumentation and Control, University of Cauca, Colombia

c. Professor, Department of Telematics, University of Cauca, Colombia

d. Professor, Department of Biology, University of Cauca, Colombia

**Corresponding author, cristianmendez@unicauca.edu.co*

Abstract

In recent years, various environmental assessment methods have been developed. The aim of this paper is to compare these methods to identify their advantages and disadvantages when used to analyze energy efficiency in agricultural production systems. A systematic review of information helped to identify six environmental assessment methods: ecological footprint, material flow analysis, ecological network analysis, life cycle analysis, exergy and emergy. A multi-criteria comparison was carried out, taking into account the level of formalization, system modeling, spatial scale, inventoried flows, type of indicators, relationship with the concept of efficiency and usability of each of the methods. This work allowed to highlight the strengths and weaknesses of each environmental assessment method. Proving that the Emergy approach, could provide a relevant framework for the analysis of the multiple energy flows that interact in an agricultural production system, and achieving an integral understanding of energy efficiency in the whole system.

Keywords: Environmental Assessment (EA), Energy Efficiency (E.E.), Agricultural production systems, criteria.

1. Introduction

The world population growth in the last century has caused an exponential increase in the resources consumption and waste emissions (Patterson et al., 2017). In response to this emergency, in the 1970s, the concept of Environmental Assessment (EA) was introduced, to analyze the state of the environment, to increase the conscience of humanity about environmental problems, and to promote Energy Efficiency (E.E.) in processes, thus contributing to build a sustainable society (Loiseau et al., 2012). Most works on E.E are devoted to offer technological solutions to industrial sectors (Trianni et al., 2014), and into a lesser extent to agricultural production systems (Jokiniemi et al., 2016; Nikolidakis et al., 2015). However, for the analysis of E.E. in agricultural production system, we suggest an integral approach that enables to evaluate agro-industrial processes behavior, and also, take into account ecosystem services, social, economic and ecological relationships existing in these systems.

Despite the development of various EA methods (Blanc and Friot, 2010), the analysis of E.E. in agricultural production systems using these tools is a complex and non-standardized task. Previous studies have compared EA methods from a sustainability point of view. For example in (Amponsah, 2011) a general review of the most used environmental analysis tools is presented. In (Loiseau et al., 2012) 9 EA methods are compared to determine which are the tools that offer the greatest advantages measuring the sustainability in a territory. In (Payraudeau and van der Werf, 2005) 11 case studies are analyzed, towards to compare 6 EA methods, with the purpose to evaluate environmental impacts and sustainability in an agricultural region; Finally, (Ness et al., 2006) provides a conceptual map categorizing the environmental assessment tools for sustainability.

The aim of this paper is to make a multi-criteria comparison of EA methods, identifying the strengths and weaknesses of these tools in the analysis of E.E. in an agricultural production system. This article is organized as follows: Section 2 presents the criteria for comparing EA tools, and the rating scale of these criteria. In section 3 the results of the comparison of EA methods are presented. Section 4 contains the conclusions.

2. Methods

Initially, a systematic review of information was carried out (Petersen et al., 2008), for this task the Science-Direct bibliographic database was used, with the next search strings: "environmental assessment and agricultural systems", "environmental accounting and agricultural systems", "Sustainability evaluation and agricultural systems", leading to the analysis of 36 articles on EA methods. Secondly, a multicriteria comparison of these methods was made by using the scale proposed (Loiseau et al., 2012): "0" no performance value is given for this criterion, because the method does not consider it; "1" the performance for this criterion is low, due to this criterion is partially taken into account by the method; "2" the performance for this criterion is good, because this criterion is included in the method, but needs improvement; "3" the performance for this criterion is excellent, because this criterion is completely included in the method.

2.1. Review of EA methods

The critical review of 36 papers (13 conceptual and 23 case studies), helped to identify 6 EA tools: Ecological Footprint (EF) (Rees and Wackernagel, 1992; Wackernagel et al., 1999), Material Flow Analysis (MFA) (Eurostat, 2001), Ecological Network Analysis (ENA) (Finn, 1976; Patten et al., 1976), Life Cycle Analysis (LCA) (Baumann and Tillman, 2005; Rebitzer et al., 2004; Tillman, 2005), Exergy (EX) (Jørgensen, 1995; Sciubba and Wall, 2007; Szargut et al., 1987), and Emergy (EM) (Brown and Ulgiati, 2004; Campbell et al., 2013; Odum, 1996a).

2.2. Criteria for comparison of environmental assessment (EA) methods applied to the analysis of E.E. in agricultural production systems

These are the criteria used to compare the six above mentioned EA methods: spatial scale to analyze the E.E., formalization of the method, system modeling, inventoried flows, multi-criteria indicators, and usability of the method; which were adopted from (Amponsah, 2011; Loiseau et al., 2012; Ness et al., 2006; Payraudeau and van der Werf, 2005). In addition, it was necessary to create a criterion to determine the tools scope in relation with the efficiency concept.

Criterion I. *Spatial scales to analyze the E.E. in an agricultural production system*: the systems are structured hierarchically (Ossa and Alberto, 2016; Von Bertalanffy, 1968), this means that the E.E. of an agricultural production system can be analyzed in a range of spatial scales (Payraudeau and van der Werf, 2005). The efficiency and sustainability from an agricultural production system affects a bigger system such as the region and in a globally way a country. Likewise, from the national scale, the country is responsible for the different energy, economic, environmental and agricultural policies that condition the functionality of the productive systems. Nevertheless, the world economy scale constrains countries development, and finally, the biosphere is the one that society should frame, since it establishes the physical environment limits and the nature finite condition (Constanza et al., 1991; Daly, 1996) (see Fig. 1-a).

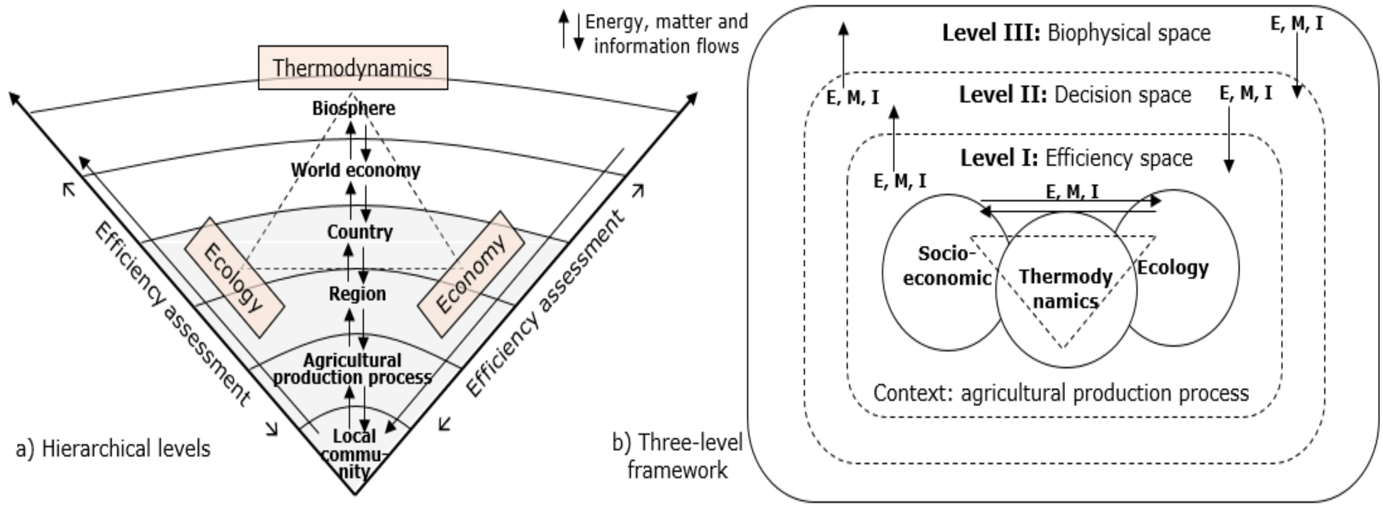

Fig. 1. a) Hierarchical levels for the E.E analysis in an agricultural production system. (Prepared by the authors). b) Framework of three levels (spatial) about efficiency concept. (Prepared by the authors, adapted from (Jollands, 2006)).

Due to the complexity of agricultural production systems (Turner et al., 2001), to analyze their E.E., it is necessary to focus on the agricultural production process scale (specifying the inputs, outputs, components and system relationships), without ignoring the interactions that occur with other systems such as the regional, country, world economy and biosphere.

Criterion II. F*ormalization of the method*: it concerns the tool standardization, due to a consensus of it allows comparisons at spatial and temporal scales of numerous studies (Barles, 2010).

Criterion III. Relationship with the efficiency concept: scope of the tool to analyze E.E. in an agricultural production system, which is consistent with the "efficiency" concept raised in the 3 spatial levels framework (see Fig. 1-b): the *level I* is the efficiency space, where a triangulation and complementarity of the efficiency concept from disciplines: thermodynamics, economics and ecology, allows to agree an interdisciplinary and integrative definition. In addition, the efficiency concept in an agricultural production system is linked to the unquestionable interaction between social-ecological systems (E, M, I flows). The *level II* decision space, seeks the application of criteria to improve the efficiency in the system. Decision making is an iterative process, with forward movements, to analyze the services and limitations of the biophysical space, and backward movements, to evaluate the probable results of efficiency derive from decision making. Level III is the biophysical space (biosphere), which configures and frames society.

Based on the conceptual framework, we propose the following concept: "Efficiency is the foundation of equity and sustainability, where the ecological limitations of natural systems and the demands on environmental services of society are valued, taking into account the decisions, the opportunity and the energy requirements for a purpose, channeling the most of part of energy available in the production of goods and/or services and avoiding the degradation of energy in possible pollutants and waste". In this concept, 4 pillars are identified: i) efficiency is a foundation of equity and sustainability, ii) valuation of ecosystem services and their limitations, iii) to channel most of the energy available in the construction of goods and services, and iv) evaluation and prevention of energy degradation in pollutants. Thus, this criterion is considered fully satisfied if a E.A method considers the four identified pillars supporting the concept of efficiency.

Criterion IV. *System modeling*: EA tools allow to make a "modeling system", quantifying the flows within the system and between the system and the ecosphere. In (Blanc and Friot, 2010) there are two approaches for modeling. The "top-down" provides a global view of the system, starting from the highest level and specifying, but without detailing the first level subsystems. The system and its subsystems are often seen as a "black boxes", and because of their high level of aggregation, these approaches are applied in the description of entire systems. The "bottom-up" works at a disaggregated level, providing a higher level of details from the set of components or subsystems that conform the larger system. The issue of a disaggregated representation is that it cannot integrate all the components of a system, for this reason, this approach often lacks of integrality, leaving aside some elements (Blanc and Friot, 2010) and leading to significant mistakes, called "truncation errors" (Lenzen, 2000).

Criterion V. *Inventoried flows*: the modeling performed by each method starts with the inventory of flows, trying to characterize from different perspectives the "metabolism" system (Ayres and Simonis, 1994). It is essential to quantify the flows that interact in the agricultural production system, to make visible the existence and contributions of ecosystem services, the human labor, and monetary flows (Amponsah, 2011). Therefore, to have a real E.E. understanding in the whole system, and the possibility of making decisions that support its sustainability. In the context from this study, three (3) flows categories are defined: i) inventory of renewable energy flows (sun, rain, wind); ii) inventory of non-renewable energy flows (land, water); iii) inventory of energy flows produced by the economy (public services, labor, machinery, chemicals, fuels, etc.)

Criterion VI. *Multicriteria indicators*: the inventoried flows in the previous criterion are used to build up the indicators (Boulanger, 2004). The indicators of each method seek to highlight the interactions between the social, environmental and economic dimensions (Ness et al., 2006). The link between human activities and environmental impacts has been represented by the DPSIR model (Drivers - Pressure - State - Impact - Response), developed by the European Environment Agency (Smeets and Weterings, 1999). The purpose of this model is to describe the relationships between the origins and the consequences of environmental problems, and it makes the differences between indicators of the environmental sphere (pressure, state and impact), and indicators of the social sphere (driving force and response) (Svarstad et al., 2008). For the analysis of this criterion, two sub-criteria have been defined: i) recognize which type of indicator does each method adopt, according to the DPSIR analysis framework; ii) analyze if the methods make a multi criteria evaluation and provide several indicators (Finnveden et al., 2009). The first sub-criterion was evaluated in a binary way: impact or pressure indicators.

Criterion VII. *Usability of the method*: The results (indicators) provided by an EA method should be practical to use for decision making, that is, be intelligible, delivering a clear and understandable message (Blanc and Friot, 2010). Also, the method usability is measured in relation with its feasibility, this makes mention of the data availability necessary for the tool implementation. Likewise, in (Weidema et al., 2008) they suggest that a simple and easy-to-use tool is more likely to be adopted by a general public.

2.3. Criteria rating scale

Table I presents the criteria and the rating scale, it explains the conditions in which each method receives a score from 3, 2, 1 to 0 points for the formulated criteria.

3. Results

Seven (7) criteria were proposed to compare the six (6) EA methods, in relation to the suitability and weakness of these tools to analyze E.E. in an agricultural production system. Based on the bibliographical review, using the criteria and the rating scale presented in Table I, the weighting of each EA method was performed, obtaining the results shown in Table II. Also, Fig. 2 presents the comparison results from the methods by radar-type graphics.

Table I. Criteria and rating scale, in relation to the analysis of E.E. in an agricultural production system.

Criteria	Rating			
	3 points	**2 points**	**1 points**	**0 points**
Criterion I	Method that promote a study on a local scale, but recognizes interactions with a larger scale	Method that facilitates a regional scale study recognizing interactions with other scales	Method that bases its analysis on a global scale, it recognizes interactions with other scales	Method that promotes only global scale studies
Criterion II	Method with international standards	Method that has an established and recognized methodology	Method with an accepted methodology, but not often used	Method that does not have a methodology
Criterion III	Method that considers the 4 pillars of the efficiency concept	Method that considers 3 pillars of the efficiency concept	Method that considers 2 pillars of the efficiency concept	Method that considers 1 or 0 pillars of the efficiency concept
Criterion IV	Method that uses "top-down" and "bottom-up" approaches	Method that uses the "top-down" approach	Method that uses the "bottom-up" approach	Method that does not use any approach
Criterion V	Method that considers the 3 flows categories	Method that considers 2 flows categories	Method that considers 1 flows category	Method that does not consider any flows category
Criterion VI	Method that performs a multicriteria evaluation in depth, providing several indicators of pressure and impact	Method that performs a multicriteria evaluation, and provides indicators of pressure or impact	Method that does not perform a multi-criteria evaluation, but provides indicators of pressure or impact	Method that does not perform a multicriteria evaluation, and does not provide indicators
Criterion VII	Method that has large amounts of data (local scale), and is intelligible to users in general	Method that has a limited number of data (local scale), and is intelligible to a specific user	Method that has a limited number of data (local scale), and is not intelligible	Method that has no data, and is not intelligible

Table II. EA methods comparison results, in relation to the suitability to analyze E.E. in agricultural production systems

Criteria	Methods					
	EF	**MFA**	**ENA**	**LCA**	**EX**	**EM**
Criterion I. Spatial scales to analyze the E.E. in an agricultural production system (SpSc)	1	2	2	3	2	3
Criterion II. Formalization of the method (FM)	3	3	1	3	1	2
Criterion III. Relationship with the efficiency concept (RE)	1	1	2	1	2	2
Criterion IV. System modeling (SM)	3	2	1	1	1	2
Criterion V. Inventoried flows (IF)	2	2	2	2	2	3
Criterion VI. Multi-criteria indicators (MI)	3	2	2	2	3	3
Criterion VII. Usability of the Method (MU)	2	2	2	2	2	2
Sub-criterion (Criterion VI)- Type of indicator	Pres/Imp	Pres	Pres	Imp	Pres/Imp	Pres/Imp

3.1. Analysis of the comparison

Criterion I*. Spatial scales to analyze the E.E. in an agricultural production system*: from the bibliographical review, there are 23 case study papers, in which one of the EA tools or the combination of two of them are applied. Table III shows the considered environmental impact dimension (environmental, economic and social), the potential users of the research results (researchers, policy makers, farmers, industrialists), and finally the analyzed scale in each study (local (L), regional (R), global (G)).

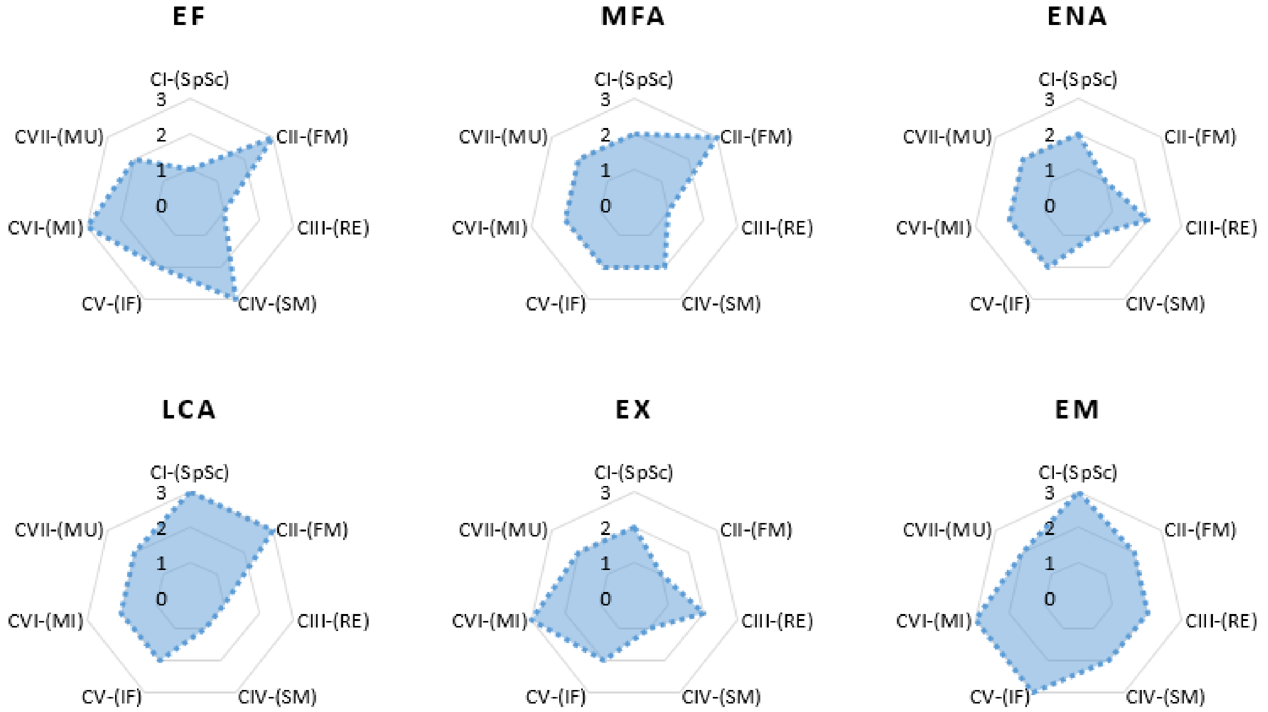

Fig. 2. EA methods comparison results, in relation to the suitability to analyze E.E. in agricultural production systems.

Table III. Case studies using EA methods, considered dimensions of sustainability, intended users, and considered spatial scale of impacts.

Methods	Paper	Dimensions considered	Intended users	Scale of impacts		
				L	R	G
EF	EF1	Environmental and economic	Farmers and researchers	+/-	+	-
	EF2	Environmental and economic	Policy-makers and researchers	+/-	+	+
	EF3	Economic	Policy-makers and researchers	-	+/-	+
	EF4	Environmental and economic	Researchers	-	-	+
	EF5	Environmental	Policy-makers	-	-	+
	EF6	Environmental	Policy-makers and researchers	-	+	+
	EF-MFA	Environmental	Policy-makers	+/-	+	+
MFA	MFA1	Socio-economic	Policy-makers	-	+/-	+
	MFA2	Environmental	Researchers	+	+/-	-
	MFA3	Environmental and economic	Policy-makers	-	+/-	+
ENA	ENA1	Environmental	Researchers	-	+	-
	ENA2	Socio-economic	Policy-makers and researchers	-	+/-	+
	ENA-EM	Environmental and economic	Researchers	-	+	+
LCA	LCA1	Environmental	Researchers	+	+	-
	LCA2	Environmental and economic	Researchers	+	+/-	-
	LCA3	Environmental	Industrialists and researchers	+	+/-	-
	LCA4	Environmental and economic	Farmers and policy-makers	+/-	+/-	+
EX	EX1	Environmental	Industrialists	+/-	+	-
	EX2	Environmental and economic	Policy-makers	-	+	+/-
EM	EM1	Environmental and economic	Farmers and policy-makers	+	+/-	-
	EM2	Environmental and economic	Farmers and policy-makers	+	+/-	-
	EM3	Socio-economic	Policy-makers	+/-	+/-	+

	EM4	Environmental and economic	Farmers and policy-makers	+	+/-	-

LCA and EM are characterized for making a local scale analysis, recognizing interactions with larger systems such as the regional one. For its part, the MFA, ENA and EX, have been commonly used at the regional level. And the EF due to having national or global databases, generally focuses its studies on a global scale.

Criterion II. *Formalization of the method:* the LCA is the tool with the highest formalization level, international standards ISO 140040 & 14044 (ISO, 2006a, 2006b); the MFA has a methodological framework developed by Eurostat (Eurostat, 2001); the EF follows the guidelines established in (Rees and Wackernagel, 1992) and defined standards by the Global Footprint Network; EM does not have a standardized framework, but it has Odum's extensive methodology (Odum, 1996b); finally, EX and ENA are two methods less formalized, which fewer cases of application were identified.

Criterion III. *Relationship with the efficiency concept:* in section 2, a new concept on efficiency was proposed, supported by four fundamental pillars. Next, in Table IV it is shown if the EA methods allow to understand each one of these pillars.

Table IV. Compliance with the pillars of the efficiency concept by EA methods.

Methods	**Pillars of the efficiency concept**			
	Pillar 1	**Pillar 2**	**Pillar 3**	**Pillar 4**
EF	✓	x	x	✓
MFA	✓	x	x	✓
ENA	✓	✓	✓	X
LCA	✓	x	x	✓
EX	✓	✓	✓	X
EM	✓	✓	✓	x

The EF offers a broad view about the sustainability level of the system, making an inventory of matter and energy flows required to support a population. However, this tool does not focus its interests on measuring the system efficiency levels (Fiala, 2008; Kitzes et al., 2009). The MFA counts the input/output materials of system and correlates them with the potential environmental damage that could cause, nevertheless, this tool does not differentiate between the various types of resources that input to the system (Eisenmenger et al., 2007). The ENA, helps to describe the system structure and function, based on the study of their interactions (material, energy and money flows) (Fath and Patten, 1999), but with this tool it is not possible to unify quantitatively the different flows. Meanwhile, the LCA makes a detailed inventory from the acquisition of raw materials to the waste disposal, providing detailed information about the impacts caused to the environment by the creation of a product or service (Baumann and Tillman, 2005; Rebitzer et al., 2004). The EX and MS focus its analyzes on the study of the energy flows of the system, the first emphasizes the part of energy that is convertible in any other type of energy (energy quality), being a very useful tool to maximize efficiency, while MS measures the energy record (solar energy used directly or indirectly) to the generation of a product or service (Odum, 1996a).

Criterion IV. *System modeling*: in the 6 studied tools, the evaluation begins with the system definition (components, interactions, limits). Considering the two modeling approaches proposed in (Blanc and Friot, 2010), the "bottom-up" prevails, since it is the one adopted by ENA, LCA, and EX. In the other hand, the MFA and EM, searching a global vision of the system, they adhere to the "top-down" approach. Finally, the EF uses both approaches to represent the system.

Criterion V. *Inventoried flows:* the EF has not been developed to provide a comprehensive overview of all environmental flows, for example, this tool does not consider interactions in agricultural processes such as flows corresponding to the human labor, and the monetary exchange (Fiala, 2008; Kitzes et al., 2009). The ENA helps to describe the system structure and interactions, but it does not allow to quantify the different flows (matter, energy and money) (Fath and Patten, 1999). The LCA makes a materials inventory, the energy inputs, and the emissions associated with each phase of the life cycle of a product or service, but leaves aside the renewable resources valuation (Baumann and Tillman, 2005; Rebitzer et al., 2004). The MFA considers the mass flows, providing a good description of a process, allowing environmental, economic and energetic evaluations of a system. However, this tool does not distinguish between different types of resources (Amponsah, 2011). The EX is a useful method to locate and quantify the energy quality losses in the processes, nevertheless, it does not provide any information on the thermodynamic record or the life cycle of the product or service, which is especially relevant in the decision making with environmental conscience (Amponsah, 2011). Finally, only EM is designed to integrate in its analysis all types of renewable resources (biomass, wind, solar, etc.), non-renewable and flows produced from economy (Barros et al., 2009; Cuadra and Rydberg, 2006)

Criterion VI. *Multi-criteria indicators:* EF, EX and EM, provide information about pressure and environmental impact, mainly related to the resources consumption. The LCA offers impact indicators (midpoint and final) on the resources consumption and the generated emissions. The MFA and ENA tools only provide pressure indicators, which limits their interpretation. Finally, the majority of tools strive to perform a multicriteria evaluation, however, LCA is the only one that deepens this objective (Loiseau et al., 2012).

Criterion VII. *Usability of the method*: With regard to the tools feasibility, all of them require considerable amounts of data, however, the LCA, EF and MFA have large databases (national or global scale). Nevertheless, when a regional analysis is carried out, the lack of data is a major obstacle shared by all the tools. On the other hand, the understanding and clarity of the tools is variable by general public, some tools such as MFA and EF use simple concepts such as the accounting of flows of matter or areas, while EX, EM and ENA are based on concepts more complex as thermodynamics and ecology.

4. Conclusions

To achieve a sustainable development, it is necessary to plan efficient agricultural production systems, that consider the management of resources and respect the natural services. Several stakeholders have used EA methods such as: ecological footprint, material flow analysis, ecological network analysis, life cycle analysis, exergy and emergy, to evaluate environmental performance at different scales, predominantly sustainability analysis. In this article, a multi-criteria comparison of 6 EA methods was proposed, in relation to the analysis of the E.E. in agricultural production systems.

The results from the comparison indicate that each tool has its own strengths and weaknesses to analyze the E.E. in agricultural production systems. This can be explained, because the EA methods make a specific system modeling, and have been developed with a specific objective. However, Emergy (EM) emerges as a promising framework for the analysis of E.E. in agricultural production systems, due to it makes an integral assessment of the energy flows that interact in the system, it is a compatible tool with the proposed spatial scale, it accomplishes with 3 of the 4 pillars proposed for the concept of efficiency, and delivers multicriteria indicators. Although EM does not have a standardized international framework, the wide and well-known methodology proposed by Odum stands out. Likewise, the modeling approach adopted by this tool is the "top-down", allowing an integral view of the entire system. Finally, the lack of data to make a study in a regional or in a lower scale is a common difficulty of the 6 analyzed methods.

In addition, the different assessment tools presented in this work can be combined, because they are complementary. For the particular case of the analysis of E.E. in agricultural production systems, we believe it would be interesting to combine Emergy with a tool such as ENA, due to it would help to understand the structure and functions of the system, also the identification of the components and the energy flows that interact. To introduce the ecological network analysis concept with the emergy accounting, would allow the integration of the different energy flows with the physical units or system components, achieving a better approach to understanding the complexity of these phenomena.

Finally, EA methods applied to the analysis of the E.E. in agricultural production systems, would provide to decision-makers useful information to support the development of agricultural, energy and commercial public policies that help to build efficient productive chains.

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