Sustainable Development, Energy Efficiency and Environmental Impacts in Coffee Farming Process

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Abstract

Efficiency and environmental impacts are key factors in the different dimensions that integrate the relationships between Energy, Territory and Development (ETD), so they can be treated as inherent characteristics of the systems under analysis, whose measurement and evaluation allows to obtain a vision about the dynamics of energy use and the use of resources while promoting the formulation of strategies to jointly achieve the maximization of the desired results and the minimization of the negative impacts associated with existing processes. This paper presents the results of the study of energy efficiency and sustainability in a sample of farms producing coffee in southwestern Colombia; This work is based on the application of a study of emergy synthesis for the use of a unit of homogeneous measurement of energy, matter and information flows. Emergy results were also integrated with data envelopment analysis (DEA) for the joint assessment of energy efficiency using the different sources, inputs, products and environmental effects, thus seeking to encourage the analysis and formulation of development strategies in the territory.

Keywords: emergy synthesis, energy efficiency, emissions, coffee production, sustainability

1. Introduction

The relationship between Energy and Development as well as its direct effect on the sustainability of territorial systems (ETD) is based on energy efficiency as a strategy to support existing processes that maximize production and minimize the negative effects of human activities (Sepúlveda, 2017); thus, sustainable development, as an objective and result of economic, productive and environmental activities in the social structures of the territories, is directly linked to the level of energy efficiency and the environmental impact of these activities.

This work then focuses on identifying tools that allow the evaluation of energy efficiency in the dynamics of the territories and their application. From the general analysis of the municipality of Pitalito in southwestern Colombia regarding the relationship between production and energy consumption, it was possible to identify a particular activity with a high impact on the different dimensions of territorial sustainability: coffee production is the main process of territory occupying about 40% of the productive area, with a contribution of 8% of the gross domestic product that represents not only an impact activity on the productive dynamics, but also an important component in the social structure of the municipality, being the main product, representative of the agricultural vocation and determinant of the identity of the territory (Ordoñez *et al*, 2013).

Coffee production also represents 16.4% of the total emergy consumption in the municipality of Pitalito, which, analyzed according to sources of origin, represents 32% of total renewable flows, 8% of non-renewable flows and 20% of the flows imported according to their average production costs (Sepúlveda, 2017) where their impact on the total emissions of the Department represents close to 30%, mainly due to emissions associated with the use of fertilizers and the transport of the product (MCCH, 2016).

Given then the specific importance of this process in the environmental, social and economic dimensions of the territory, through emergy synthesis (Odum, 1996) the flows linked to its productive process were analyzed with the aim of evaluating at the lowest level of detail (farms) the factors of efficiency and environmental impacts; Likewise, data envelopment analysis (DEA) was applied to calculate the energy efficiency of each producer, which allowed to identify a general strategy for the increase of the efficiency in the crops, as well as the patterns and the behavior of the efficient territories. Also, the generalities of the inefficient territories were described and potential values of improvement in their processes were identified.

2. Methods

To evaluate the interrelation of ETD in a group of coffee farms located in the municipality of Pitalito in the Department of Huila, there was an integration of emergy synthesis principles (Odum, 1996) and data envelopment analysis DEA (Restrepo and Villegas, 2007). Fig. 1 shows the emergy diagram for coffee processing in these territories showing the main flows, components and connections, starting with the resources provided by nature, whose value was determined by calculating the flows contributed by the rain.

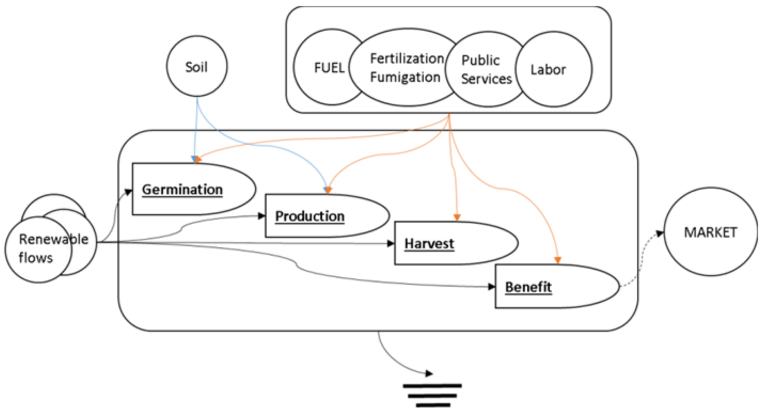

Fig. 1. General Systemic diagram for coffee production

Within the diagram there are four processes:

- **Germination**: Performed by 46% of the producers, this process is the first stage of the vegetative growth of the coffee tree and is carried out for a period between 70 - 80 days, when the plant is transferred to the nursery. (CENICAFÉ, 2013a).
- **Production** and **harvest**: At this stage, two coffee growing states are considered. The rise, which corresponds to plants under 16 months and in production that corresponds to older plants (Arcila, 2007).
- **Benefit**: Corresponds to post-harvest activities, including pulping, washing, fermentation and drying coffee to produce Dry Parchment Coffee.

In this study only the stages of production, harvest and benefit are evaluated. For the quantitative analysis of the flows a sample of 90 farms and producers was taken, the selection criteria corresponds to the complete availability of relevant data to complete the study of emergetic synthesis given the variability in the response rates obtained in the field work, covering with this study an area of 396 hectares corresponding to 0.63% of the municipality of Pitalito and 2% of the area sown with coffee trees in the territory.

Renewable resources (R) were evaluated through the average rain in the territories, non-renewable resources (N) are mainly represented by the loss of soils and Imported flows (F) correspond to the resources, services, products, processes, machinery and equipment that are linked to the coffee processing in the system under analysis (Brandt - Williams, 2002), this results were also compared with similar studies applied to the coffee process, looking for the possibility of identifying patterns and values against existing results applied to coffee production, although implemented in different geographical scenarios such as Nicaragua (Cuadra & Rydberg, 2006), Brazil (Giannetti *et al,* 2011), Peru (Suca, *et al*, 2012) and Colombia (González, 2015).

For DEA, a DEA-BCC model oriented to inputs and with variable returns to scale was applied (Restrepo and Villegas, 2007), this means that the applied model seeks to find the maximum possible reduction in the vector of inputs. (emergy flows R, N, F) while the dynamics of production of the territories (farms) remains (Production, emissions and Environmental sustainability index ESI). Under this model, a farm is not efficient if it is possible to reduce the use of its emergy flows without altering its production, its environmental sustainability index or its emissions; To measure the performance of each farm the model seeks to maximize the relative technical efficiency defined as the relationship between the weighted sum of the outputs and the weighted sum of the inputs, which is evaluated in a scale between zero (0) and one (1), the latter being the highest level of efficiency possible. An additional consideration of this proposed model is that the emissions should be considered an undesired output and therefore, it was necessary the transformation of the unwanted output using the model proposed by Seiford and Zhu (2002). The final calculation of the efficiency results was made using the DEA solver tool developed for the Excel platform by Jablonsky (2008).

3. Results

2.1. Process and emergy flows

Renewable flows

Coffee as a product can be considered as the result of an intensive process dependent on the interaction between different flows of resources in three categories: environmental, genetic and management, whose integration increases the productivity of the crops (CENICAFÉ, 2013b). According to the analysis carried out in the municipality of Pitalito, the greater environmental emergetic flow is calculated from the values obtained by the rain and its transforming potential of the environmental systems. This value shows the effect of the different geo-bio-physical forces existing in the territory (Odum, 1996), so that the assessment of the emergy content of rainfall allows quantifying the total contribution of nature, although it does not allow distinguishing the independent effect of each flow or environmental condition.

In the 90 cases analyzed, 80% of the total renewable flows are concentrated in the range between 7.66E+14 sej/year and 1.22E + 16 sej/year with an average value of 1E+16 sej/m^2. There is a great concentration of contribution in farms of small producers. 30 farms (33.3%) have a higher consumption of renewable streams (over the average); the highest value obtained in the study is 3.7E +16 sej/year for farm 158, characterized by having a size of 12 ha, located at a height of 1563 m a.s.l with 9.2 ha planted in the sun in 8 lots of coffee trees and 45,000 plants in production stage with an average age of 41 months. While the lowest value corresponds to the sample unit 292, characterized by being located at 1558 meters above sea level, having a size of 4.5 Ha with only 0.19 ha planted in the shade in 3 lots of coffee trees with an average age of 36 months, combining "*Castillo*" and "*caturra*" varieties, this farm sells 100% of its production to private companies and participates in special coffee events, which may explain the low density of sowing and production area.

Non renewable flows (N)

In Colombia, the loss of soils is mainly related to water erosion, the formation of gullies, mass movements and pollution (CENICAFÉ, 2013b). In the case of coffee, several studies have been identified related to soil loss that establish a relationship between this and the natural erosive processes of rainfall, but also anthropic causes such as the particular productive dynamics of the territory, including weed control (Gómez, 1986), the type of crop, the farming practices (Agudelo *et al,* 2015) and the inadequate management of resources (Salazar and Hincapie, 2006).

From the work of González (2015), a soil loss value corresponding to 5 $tonha^{-1}year^{-1}$ was determined in polycultures and 20 $tonha^{-1}year^{-1}$ in intensive systems. Likewise, regarding the loss of nutrients, a Cenicafé study prepared in the 1980s raises several values for the loss of minerals in the soil, due to erosion according to different sowing scenarios. In this, values between 1 and 27 kg of lost minerals were found, including Nitrogen, Phosphorus, Potassium, Calcium and Magnesium in bare or covered soils and dense shade, showing a lower loss in crops with use of cover and shade (Cenicafé, SF). González (2015) in his study quantifies these values around 3 $kgha^{-1}year^{-1}$ in polycultures and 15 $kgha^{-1}year^{-1}$ in intensive systems.

The emergetic flow was calculated due to the loss of soil and nutrients, which is comprised in the range 9.38E+13 sej and 1.82E+16 sej, it is important to highlight a key element in the relationship between the loss of soil and the productivity of coffee. Studies carried out in Colombia, have been able to demonstrate how the level of erosion affects the productivity of the coffee lots, with reductions in the productive level of the plants up to 60% in cases of severe erosion, and the increase in costs due to the need of fertilizer integration due to the loss of nutrients in the soil (CENICAFÉ, 2013b) which explains the high level of efficiency of nature in the distribution of their contributions to production systems.

Imported flows (F)

The imported flows, or subsidized flows (Jordan, 2013) identified for the productive process analyzed include: Fertilizers, Pesticides and Fungicides, Labor, Electricity and Fuel. In this study due to practical limitations of the instruments used, and the difficulty of accessing specific information, subsidized flows such as technical services, farm management or packaging were not analyzed, however, it is assumed that the overall impact of the studied flows is strong enough to have a general idea of the productive dynamics and the energy consumptions linked to the process.

In the case of fertilizers and the use of insecticides and fungicides, two scenarios were analyzed according to the type of production (organic or traditional), although most of surveys (85 cases out of 90) show that traditional production is being the dominant pattern in the territory. For labor, the average daily wage was taken for cultivation, maintenance and harvesting of coffee trees per hectare in accordance with the production cost structure in SIRHUILA (Gobernación del Huila, 2016) and for the calculation of flows from electricity and fuel, according to the use of these resources measured in producer surveys. The average value for imported flows was 1.51E+15 sej, with a maximum value of 5.6E+15 and a minimum of 1.22E+14 sej. Regarding the cost structure and the contribution of the individual flows, Table 1 shows the percentage share of each flow in the total consumption of subsidized resources.

Table 1. Participation of each item in the calculation of subsidized flows.

Flow	Value (sej)	Participation
Total Fertilizers in growing (organic)	2,69952E+13	0,02%
Total fertilizers in production (organic)	6,03267E+13	0,04%
Total Fertilizers in growing (Traditional)	1,03465E+14	0,08%
Total fertilizers in production (Traditional)	1,89642E+15	1,40%
Total Pesticides and fungicides	8,9392E+15	6,58%
Total work and labor	1,18925E+17	87,55%
Total Electricity	2,45998E+15	1,81%
Total fuel	3,41985E+15	2,52%

According to the results, the specific weight of the labor force can be appreciated in the total consumption structure of subsidized flows, which directly impact on the productivity of the territories, the quality of the product and the income obtained by the producers (Duque & Dussán, 2004). Another important value is shown in the line corresponding to pesticides and fungicides used in the phytosanitary control of pests and diseases: Low values in fertilizers can be associated with the contribution of land and territory in terms of the quality and existence of specific nutrients for the crop. In the case of fuel and electricity use, a pattern of short trips with an average of 13 km between the farms and the selling sites was observed in the analyzed samples.

Emergy sustainability indicators

Based on the results obtained, Table 2 shows the summary of the indicators studied to evaluate the sustainability of the territorial systems

Table 2. Average value of emergy indicators for the analyzed territories.

Indicator	Expression	Average value
Renewable Flow	R	1,00E+16
Non-Renewable flows	N	3,40E+15
Imported flows	F	1,51E+15
Total emergy consumption (U)	N0+N1+R+F	1,49E+16
Derived from local sources	(NO+N1+R) /U	0,899
Local renewable sources	R/U	0,67
Fraction that is bought	(F)/U	0,10
Consumption per area	U/ (area ha)	6,58E+13
Environmental loading ratio (ELR)	(Imp + N0 + N1) / R	0,49
Environmental Yield Ratio (EYR)	U / (N0 + N1 + F)	3,04
Emergy sustainability index (ESI)	EYR / ELR	6,20

Table 3 shows the value identified for the emergy sustainability indexes in four referenced studies and the results calculated in it. The ELR, which shows a value of 0.49, in some way manifests a high degree of sustainability in the analyzed territories, which demonstrates the value of natural resources in the territorial dynamics linked to coffee production, being the lowest value compared to the cases found in the literature.

Table 3. Comparison of emergence sustainability indexes for coffee.

Territory	ELR	EYR	ESI
Nicaragua (Cuadra y Rydberg, 2006)	8,5	1,12	0,13
Brasil (Giannetti *et al*, 2011)	8,1	1,13	0,14
Perú (Suca *et al*, 2012)	1,01	2	1,99
Colombia (González A, 2015)	1,5	1,9	1,26
Pitalito	0,49	3,04	6,20

This tendency is reversed in the case of EYR, suggesting that in Pitalito, the processes related to coffee production are mainly based on local resources. ESI allows seeing how the dynamics and structure of the processes linked to the production of coffee in the territory imply a model of long-term sustainability of production.

2.2. Energy efficiency

DEA Model

Each territory (farm) represents in this study a decision-making unit (DMU). The inputs analyzed correspond to the emergy flows, in the outputs, production was chosen, as the direct result of the effort made by coffee growers. For outputs: the ESI as a sample of the long-term relationship between people and the territory and emissions, given the interest of this project to integrate the efficiency and the environmental impacts in the measurement.

In the emergetic analysis of the territories, the calculation of emissions was not carried out, however in the study of the processes associated with coffee production in the municipality of Pitalito, a preliminary value of emissions corresponding to 23.47 Kg CO_{2eq} has been found for each kg of dry parchment coffee. This value does not yet include the weight associated with the transportation and fuel use activities, however, the main weight in these evaluations is given by the contribution of loss of soils, fertilizers and associated chemical products, but without considering removals. Taking a transformity value of 1.57E11 sej/g (Kursun, 2013), the information related to emissions was completed. In Table 4 it is shown a sample of the configuration of the data used in the DEA-BBC model applied.

Table 4. Sample Input values for DEA

		Inputs			Outputs		
		R (sej)	N (sej)	F (sej)	Production (sej)	Emissions (sej)	ESI
1	Farm150 (Prueba 150)	7,67E+15	9,65E+14	1,08E+15	1,43E+16	1,77E+19	17,82
2	Farm142 (Prueba 142)	7,69E+15	9,65E+14	1,10E+15	1,43E+16	1,77E+19	17,63
3	Farm183 (Prueba 183)	9,63E+15	1,24E+15	1,42E+15	1,84E+16	1,77E+19	16,69

Table 5 shows the sample of results obtained with the DEA solver; these are organized from left to right in the following way:

- ID: Number ordered by the application to each DMU analyzed
- DMU: Identification of each production farm studied
- EFF score: Value of efficiency obtained in the evaluation
- Virtual inputs: Value calculated for the inputs, may vary from the original value, corresponds to the value that increases its efficiency
- Virtual outputs: Value calculated for the outputs, may vary according to the model used
- Pears: Pairs, in each DMU or territory studied, the model proposes up to 5 comparative pairs that are units with the highest efficiency and whose strategies can be implemented to improve the efficiency of each DMU analyzed.

Table 5. DEA efficiency study results sample

	DMU	**Eff. score**	**Virtual inputs**			**Virtual outputs**					
Id			**R**	**N**	**F**	**Produc.**	**Emiss.**	**ESI**	**Pears --->**		
1	**Farm93 (Prueba 93)**	0,93	5,8E+15	8,3E+14	8,6E+14	1,3E+16	1,7E+19	17,80	30	63	65
2	**Farm221 (Prueba 221)**	1,00	6,6E+15	3,6E+15	1,1E+15	3,5E+16	1,0E+19	3,25	2		
3	**Farm110 (Prueba 110)**	0,95	4,9E+15	6,7E+14	7,5E+14	1,2E+16	1,6E+19	17,04	16	63	65

The results can be read for the first sample (also identified as “prueba”): The DMU farm93 reached a technical efficiency of 0.93; in its current conditions for the increase of its qualification it can be compared with units 30, 63 and 65, reaching a potential of reduction in the use of renewable resources of 6%, 7% less use of non-renewable resources and 24% less use of imported resources, maintaining current production and emissions and increasing its sustainability index by 42%.

2.3. Results analysis

With DEA, 17 efficient units were identified, corresponding to 19% of the territories studied; it can be said that in principle they are quite heterogeneous, for example, 41% of them carry out the planting in the sun system, the size of the lots also vary, having representation of small-holder, small, medium and large producers, the distance of planting or fertilization decision making based on soil analysis or the use of agrochemicals.

The only two common factors explicit in this group are the acceptance of special coffees as a strategy for developing their product and economic growth and the application of a traditional non-organic farming system; however, only 5 of these producers have participated in special coffee events. Given these marked differences, it became necessary to use statistical analysis to identify strategies and common patterns in the behavior of the territories that are referring to efficiency according to the results obtained in DEA. Fig. 2 shows the result of the applied conglomerate test.

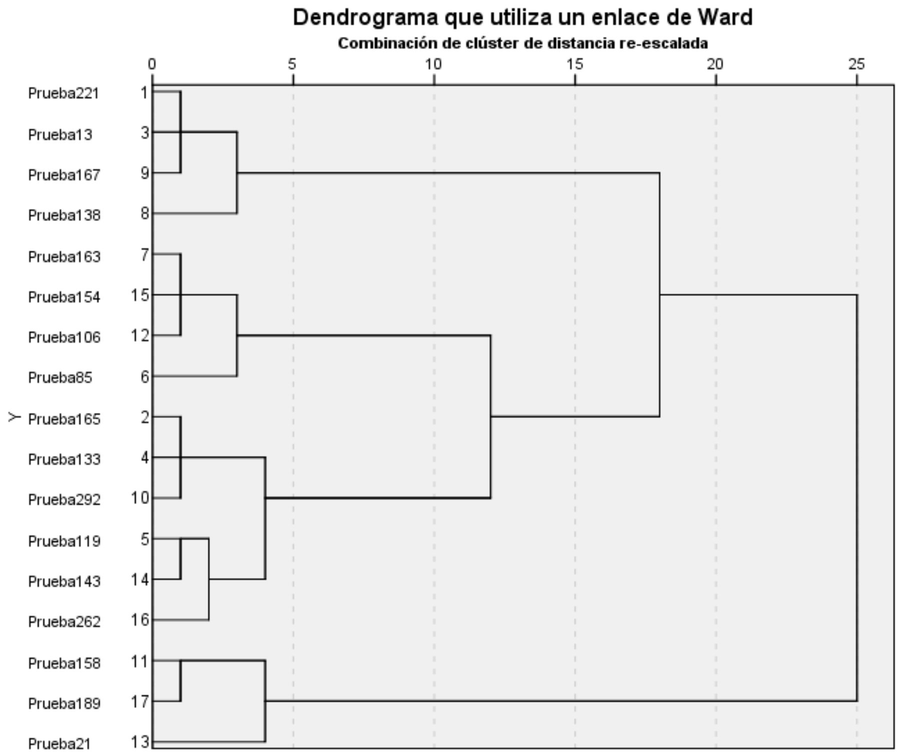

Fig. 2. Conglomerate analysis in Pareto efficient territories with SPSS

The first thing that can be appreciated is the conformation of 4 groups (they will be named from top to bottom as group 1, 2, 3 and 4) in the 17 efficient territories studied. Regarding the use of resources, two strategies were found:

- Groups 1 and 4 have on average a use of natural, non-renewable and imported resources of 60%, 30% and 10% respectively
- Groups 2 and 3 have an average usage of 80%, 10% and 10% respectively in these same flows.

This first identified pattern allows establishing the importance of the use of natural resources in the technical efficiency of the processes related to the sowing, cultivation and harvesting of coffee. When analyzing the percentage corresponding to the imported flows, which is constant in both groups, two different strategies can be seen: one, based on the orientation of the processes towards a greater use of natural resources and the other, towards the increase of productivity based on the non-renewable exploitation of resources. This can be further verified with the analysis of the environmental sustainability index (ESI), which is between 16 and 20 for groups 2 and 3 while in groups 1 and 4 it is in the range 1-8 with an average of 3.

All farms in groups 1 and 4 have their crops in systems under the sun and 100% of them said they carry out soil studies as support for their activity while, groups 2 and 3 plant in shaded systems and only 60% of These producers perform soil study. According to Cenicafé (2013b), planting density and shade are key factors in the amount of fertilizer required to raise coffee productivity. Regarding the planted area, groups 1 and 4 are different in size, being the first small producers with an average area of 1.33 ha of cultivation and the second, large, with an average area of 7.94 ha. In the case of groups 2 and 3 corresponding to producers with shade crops, the averages are 5.57 ha (Medium) and 0.9 ha (Small) respectively.

About the inefficient units, these have an average of 0.82, demonstrating in general a high level of use of resources in the territory, with a data range between 0.43 and 0.99. The most inefficient unit is that identified as Farm132, which is a 7ha farm with 4.8ha dedicated to the cultivation of coffee trees in the sun, located at 1500 m a.s.l. The distribution of consumption of this farm shows a value close to 60% for renewable flows, 30% for non-renewable flows and 9% for imported flows, the same trend presented in group 4; However, this efficiency value is not due to the dynamics of its practices or processes, in this particular case, 66% of the trees planted have an age manifested by the producer of 3 months, which implies consumption of resources without productive returns in the short term, therefore, the level of efficiency achieved is due to the imbalance between new trees and trees in the production stage.

Given that the model used was oriented to the inputs, the output variables were not modified in the analysis of results while the input values decreased, showing that all the analyzed territories are able to reduce their emergy consumption while maintaining the current production levels, the analysis of the results shows an average potential reduction of 32% for renewable flows, 49% for non-renewable flows and 35% for imported resources, the latter two having the greatest impact on the sustainability of the territory.

These last components of the analysis also show that the measure of efficiency cannot be separated from a case-by-case study of the particularities of the territory, for which reason, the formulation of strategies and the taking of specific decisions related to technical change, implementation of technologies, the adoption of improvement mechanisms, cultural changes and, in general, all available options to take advantage of the productive potential of the territory, must take into account the dynamics of the systems analyzed, as well as the logic of the proposed changes and the implementation term.

Conclusions

Emergy synthesis allowed to study the productive dynamics and the existing processes in the territory. This model, already proven as a reference in the joint study of the ETD interrelations, facilitated the analysis of the territorial system, allowing to obtain a unified vision of the different energy flows that make up the productive systems according to the sources of origin, which allowed studying, quantifying and compare the dynamics of use and exploitation of existing resources in the territory. This model presents a series of efficiency indicators for the systems evaluated; however, these did not integrate the measurement of the different energy flows in relation to the productive results, the sustainability of the systems and the environmental effect of the existing processes on the environment. Thus, it was necessary to integrate the emerging synthesis model with the data envelopment analysis model (DEA) for the study of technical efficiency in territorial processes based on multiple inputs (energy flows) and multiple outputs (production, sustainability and effects). environmental) favoring the comparative analysis of the different cases studied for the formulation of strategies and the identification of the key factors for the sustainable development of the territories.

In the case of coffee, the main crop and economic activity in the territory, there was a high dependence on the product against environmental, genetic and management conditions. The quantification of the contributions of nature made it possible to establish how, in most of cases, there is an approach to take advantage of the use of these resources, which are free; although, on the other hand, the detailed analysis of efficiency in the cultivation processes also showed that the harvesting actions are as varied as the number of existing producers.

Coffee presented a low environmental load index, which shows that the processes related to its production are mainly based on local resources, where the use of energy flows provided freely by nature, in production models oriented to efficient use of the available energy and the integration of tools and knowledge to reduce the associated impacts imply a long-term development and sustainability model, making it possible to maintain current production levels, reduce emissions and increase the sustainability index in the productive activity of the territories. In this way, the results show how the efficient use of resources is translated in parallel into productivity and sustainability.

The study of the production strategies in the territories qualified with the highest level of efficiency showed, first, that the maximum use of free resources is a constant in the productive strategy. Additionally, it was found that the use of resources for production based on imported flows (fuels, agrochemicals, fertilizers, etc.) shows two differentiated strategies: one, based on the orientation of the processes towards a greater use of natural resources and the other, towards the increase of productivity based on the non-renewable exploitation of resources. Here, the evaluation of these aspects allows not only the objective measurement of the processes, flows, effects and interactions existing in the studied systems, but also allows then the planning, the development of scenarios and the decision making on the system.

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