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Sustainability improvement of coffee farms in Valle del Cauca (Colombia) through system dynamics

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Abstract
Given the problems generated in the coffee supply chain and identifying the central problem as its low sustainability, especially in Valle del Cauca (Colombia), it is imperative to propose solutions to the current development of this chain, especially about producers, which are the least benefited. These solutions should allow for balanced growth and be aimed at making it possible to overcome the current socioeconomic system based on predatory and competitive growth at the service of private interests. Thus, sustainability should trigger a profound rethinking about human groups relationships, among themselves and with the environment, betting on cooperation and defense of the general interest. The purpose should not only be the economic growth of companies, many times increasing the poverty of the inhabitants of the region or the environmental risks, but it should also be the wealth of all the involved parties. In our ongoing research, we plan to use dynamic simulation to evaluate alternatives that consider the sustainability of coffee farms, including elements of profitability, environmental impact, and social development. Preliminary simulation results are shown. This approach should ultimately allow us to find applicable and quantifiable solutions for a sustainable balance in the fundamental links of the coffee supply chain in the northern region of Valle del Cauca, Colombia.

Keywords: Coffee, supply chain, sustainability, system dynamics

1 Introduction

Currently, there is a lot of research on supply chain modeling, most of it with the main purpose of minimizing costs such as inventory, transportation, storage, material handling, among others. Less research is devoted to sustainable supply chain modeling that considers the balance between economic, social, and environmental aspects (Drake and Spinler, 2013). The integration of these components generates modeling complexity. Brandenburg et al. (2014), Carter and Rogers (2018), and Kannegiesser and Gunter (2013) have conducted literature reviews where the little use of modeling for the analysis of sustainable supply chains that simultaneously include economic, social, and environmental elements is evidenced. In the characterization by Sasikumar and Kannan (2009) and the adjustment made by Brandenburg et al. (2014), supply chain models are classified into mathematical programming methods; simulation methods such as system dynamics, heuristic methods, and hybrid models; and, finally, analytical models such as game theory, multi-criteria methods, and systemic models. Some of the tools that have gained relevance in recent years as methodologies for the analysis of complex problems are the systemic approach and system dynamics.

System dynamics is a methodological paradigm for the investigation of complex systems and is considered a subset of the broader paradigm of simulation models (Meadows and Robinson, 1985). In the process of analyzing the sustainability of the coffee supply chain, many elements can be ignored. However, according to Forrester (1987), to understand a system, it is preferable to incorporate variables and interactions even if their representation is difficult and to avoid omitting them, even knowing their importance in the performance of the whole. The idea of this approach is to be able to evaluate in a novel way the impacts of possible management and policy interventions and to observe changes in complex systems Sterman (2001), Thornton and Herrero (2001), and Tedeschi et al., 2011). This paper uses the systemic approach and the system dynamics proposed by Forrester (1987) to analyze some economic, social, and environmental aspects within the coffee supply chain in Colombia that could contribute to its sustainability.

2 Literature Review

Figure 1 shows the connections between articles on 'sustainable supply chains', a first category for reference search. The larger the node size, the more publications are associated with them. The colors represent the year of publication. There is a large volume of publications in sustainability with very similar topics such as carbon footprint, climate change, and life cycle assessment. The graph shows very few social elements; perhaps, more recently, the topics of urban agriculture, food security, and circular economy have been addressed. System dynamics appears as a tool for supply chain sustainability analysis.

In the second category, the keywords 'sustainability and supply chain and coffee' were used, from which 50 documents were obtained. For the bibliometric analysis, only one repetition of keywords was used, since there are very few documents that explore alternatives to improve the sustainability of the coffee supply chain. However, bibliometric analysis showed that coffee certifications, governance, and fair trade are the most researched topics in the search for sustainability in the coffee supply chain.

In the last category of 'applications of system dynamics in coffee supply chains', much fewer articles were found. To illustrate, Díaz and Córdoba (2019), carry out a causal analysis in the coffee agricultural system in Cundinamarca, Colombia. With the help of the community, they identified and validated the connection of relevant variables. The authors selected 54 variables in which social, economic, agronomic, and agroclimatic elements were considered, with a focus on the quality of the bean, social capital, the effect of shade on the crop, and the diversification of income from the fruits of the trees used for shade.

A dynamic simulation model was developed by Rachman et al. (2014), who included social, economic, and environmental aspects in the supply chain of Gayo coffee in the province of Aceh, Indonesia. Changes in price, demand, and environmental terms and the effect of certifications were considered. They analyzed the production of an organic fertilizer from the residue of coffee cherry pulp and showed the effect of education and training in social terms. A sustainability indicator of the coffee supply chain is defined, and improvements are evidenced after intervening key factors.

Malik et al. (2019) formulated a model of influences to achieve a sustainable production system in smallholder coffee farmers in Pangalengan, Indonesia. This work seeks to identify the drivers of economics, social quality, technology, and environmental quality that most influence the sustainability of the chain by observing compensating and reinforcing relationships through dynamic interaction. The article concludes that social quality is the most influential driver, and that social quality management and intervention strategies are needed to guarantee sustainability. Hakim et al. (2020) developed a system dynamics model for the supply chain of Gayo Arabica coffee in Indonesia, which seeks to simulate the effects of a hybrid production system, quality engineering, governance, climate change, productivity, and competition on the profitability of the chain. In contrast to Malik et al. (2019), none of the analyzed scenarios generated significant improvements for smallholder farmers.

More recently, Bashiri et al. (2021) investigated the sustainability risks in the Indonesia-UK coffee supply chain by means of systems dynamics combined with multicriteria methods. The authors concluded that improving agricultural productivity is crucial for the coffee supply chain sustainability and that the combination of the applied approaches is better than applying a single tool.

According to the above review, the study of sustainability elements associated with the coffee supply chain using system dynamics is a novel topic and deserves more research.

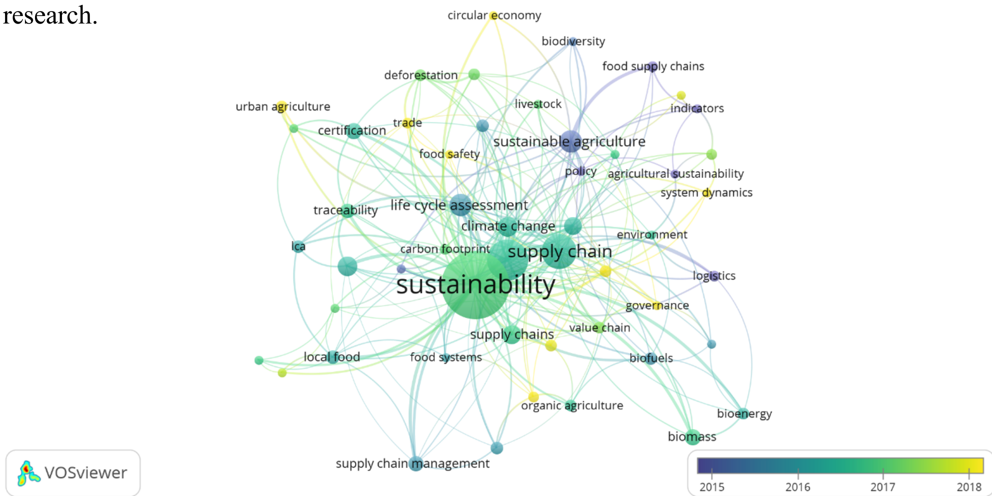

Fig. 1. VOSviewer bibliometric networks of 474 scientific articles on coffee supply chain sustainability from Scopus

3 Problem Statement

The coffee supply chain in Colombia has several drawbacks such as the instability of the international price. According to the National Federation of Coffee Growers (FNC 2018) of Colombia, the grain cost per pound went from $ 1.60 in November 2016 to $ 1.00 in May 2019, and although in 2020 and 2021 the price has had rallies above $ 1.30, there are semesters when the price generates low income in many cases below production costs. Nowadays, coffee multinationals pay 67% less than the price of coffee in 1983 and, although Colombia is the third largest coffee producer in the world and annually the coffee market generates about US$200,000 million worldwide, producers only have access to less than 10% of that figure (FNC, 2018). Although international reference prices can go down, in coffee shops and supermarkets the cost rises progressively. It is calculated that for every pound of coffee sold in the world, producers receive only 7 cents per dollar (FNC, 2018). This situation is exacerbated by other problems along the entire supply chain such as logistics costs, especially for producers. According to the national logistics survey (Encuesta Nacional Logística 2018), logistics costs in agricultural companies are around 12.8% of sales in Colombia, concentrated mainly in storage costs with 35.9% and transportation costs with 33.3%.

Another problem is the lack of generational replacement, as confirmed by data from the ceding process registered in the Coffee Information System (Sistema de Información Cafetera-SICA) of the FNC. Between 2005 and 2011, around 3,600 coffee growers in all municipalities were registered, but only 10.2%, a total of 367 growers, were under 35 years old (FNC, 2011). At this rate of 10% of new young producers per five-year period, it would take more than ten decades to replace the generations of retiring coffee growers. An additional problematic situation is the replacement of other less sustainable agricultural activities that generate more carbon footprint in the atmosphere, such as cattle raising.

The next problem refers to the lack of additional income on coffee farms to compensate for the seasons of low coffee prices, in addition to the lack of fair trade throughout the entire supply chain that equitably distributes the coffee value chain. According to Potts et al. (2007), although future markets are responsible for establishing the general price context for physical transactions, the ability of producers to impose prices that meet domestic production costs or the costs of maintaining sustainable living standards is also dependent on their capability to negotiate desirable conditions directly with buyers. Producers are often price takers with little capacity to influence the terms of trade in which they participate.

Héctor Fabio Cuéllar, director of the Coffee Growers Committee of Valle in July 2017 stated that, "In the Valle del Cauca (Colombia), 39 of the 42 municipalities grow coffee, especially El Águila, Ansermanuevo, Sevilla, Caicedonia, and Trujillo. The Valle del Cauca has 62,968 hectares planted, less than the 70,000 hectares registered some years ago; of the total, 37,000 hectares are planted with specialty coffee varieties". This shows that the problems of the coffee supply chain have a very strong influence on the families of Valle del Cauca; concretely, 23,500 families depend on this activity in our department.

To contribute to the sustainability of the coffee supply chain in Valle del Cauca and mitigate or reduce the effects of the problems evidenced here, it is necessary to propose alternative solutions and evaluate the results until a significant improvement in sustainability is achieved. This work proposes an influence diagram and its related Forrester diagram to evaluate such alternatives.

4 Methodology

4.1 Influence Diagram

A diagram of influences was made in which six reinforcement loops were clearly found (Figure 2). The first one (R1) shows the importance of the permanence of the farmers in the field, the more areas cultivated with the influence of technology, and the improvement of the quality of the coffee bean; so, more income is obtained, improving profitability. The reinforcement loop 2 (R2) shows that the more coffee growers, the less farmer migration to cities, therefore more generational replacement, thus ensuring that employment levels are not reduced in the cities and that consumption is guaranteed, which in turn promotes the purchase of coffee. Because coffee prices are not stable, it is important to compensate the likely reduction in profits with additional income in coffee farms, such as beekeeping, tourism, and pig and chicken raising. Clearly, there are other activities that currently interact with the coffee crops in several coffee farms, although the above three have been selected as the most applicable. In reinforcement loop 3 (R3), investment in tourist attractions on the farms could increase tourist visits, increasing income. Similarly, in loop 4 (R4), the more investment in beekeeping technification and good practices, the greater the production of honey and its derivatives, and therefore the greater the income. The last alternative that was included to increase the income of coffee farmers is the raising of small-scale production animals, such as pigs and chickens. In reinforcement loop 5 (R5), it is observed that if this type of farming is increased, additional income could increase.

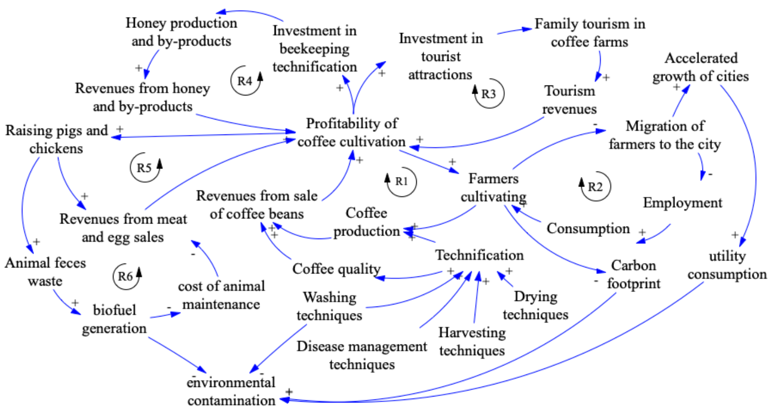

Fig. 2. Influence diagram of the coffee grower link in the coffee supply chain

It is important to note that all the previous loops are constrained by the availability of resources, such as land, water, energy, etc. Animal husbandry has another benefit, in addition to income, which is the generation of biofuel from the waste generated by animals. Many coffee growers cook using firewood, a practice that has several implications. The first is the environmental impact of burning wood. The second is the amount of labor used by farmers to collect firewood, time that can be used in activities related to the crop. Finally, firewood cooking may cause chronic respiratory diseases due to smoke inhalation. Thus, as can be seen in reinforcement loop 6 (R6), the production of more animal waste increases the generation of biofuel that contributes to the reduction of farm costs not only because of the savings in the cooking food method, but also because the biofuel can be used for drying coffee, among other uses.

The diagram of influences shows other important relationships in the sustainability of this chain, such as the utilization and transformation of animal waste into biofuels, avoiding greenhouse gases such as methane, as well as the contamination of aquifers and rivers where these wastes end up. The diagram shows that the technification in all the coffee processes of cultivation, harvesting, and post-harvesting could improve the quality of coffee. Therefore, the coffee could be placed in the market at a better price, in addition to an increase in productivity and yield, generating greater income per hectare planted. Finally, it is observed that the more farmers are cultivating, the greater the reduction of the carbon footprint due to the number of coffee and shade-generating trees planted to improve coffee quality. In the social aspect, we analyze the growing problem in Colombia due to the lack of generational replacement in the countryside. If the coffee farms are profitable, the probability of farmers' migration to cities could be reduced. Migration generates a serious chain effect, producing overpopulation in cities, therefore increasing the environmental damage by the excessive use of resources such as water and energy. In addition to the generation of waste, migration generates less production in the countryside and more dependence on imports affecting food security and the balance of payments.

4.2 Forrester Diagram

The Forrester diagram was made according to the influence diagram and the result is shown in Figure 3. There are three level variables associated with coffee production, the generation of greenhouse gases (GHG), rural population, and the profitability of coffee farms based on income from coffee sales and the other types of income proposed. The growth or decrease of the rural population based on the increase or reduction of income in the coffee farms is to be analyzed. Finally, we would like to observe the environmental impact of firewood burning reduction through the generation of methane gas by biodigester, as well as the reduction of methane gas emissions to the atmosphere due to animal waste and decomposition of the leachates produced by coffee washing. Information will be collected through field work on coffee farms associated with the variables included in the model. This, together with updated statistical and technical information, are expected to increase the accuracy of the data to obtain simulation results regarding the social, economic, and environmental dynamics suggested in this study. We thus expect to strengthen the decision-making processes associated with increasing the sustainability of the coffee supply chain.

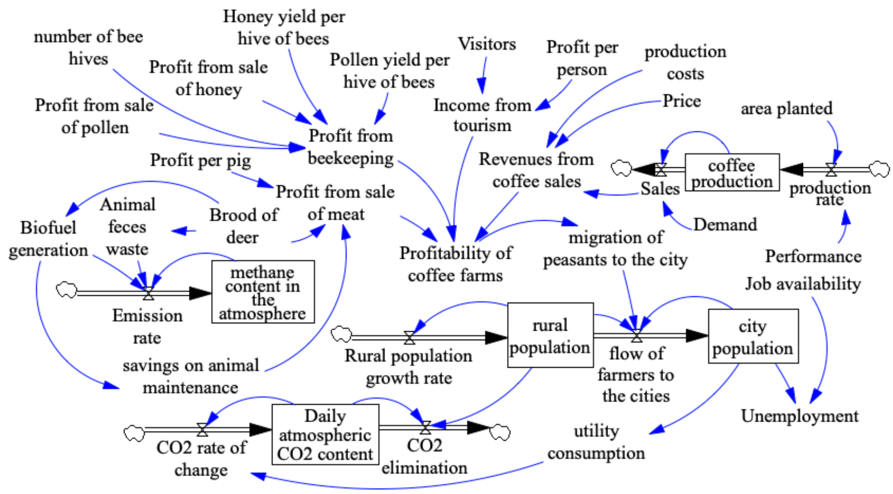

Fig. 3. Forrester diagram of the coffee growers' link in the coffee supply chain

5 Some Selected Simulation Experiments

We have gathered information about some variables from the Forrester diagram; these variables have been simulated to obtain their preliminary behavior at one typical farm. The simulation results indicate that it is important to report on these earliest research advances. Our ongoing research concentrates on the influence of the simulated variables on the non-simulated ones and their correlation. The simulated scenarios considered the following aspects:

- Scenario 1: Only coffee bean production and sales variables for coffee producers.
- Scenario 2: Alternative income sources at coffee farms such as the sales of beekeeping products, farm tourism, and pig raising / meat sales.
- Scenario 3: Some negative environmental impacts at coffee farms and their possible mitigation.

Technical and statistical information was gathered from secondary sources for 60 months (from July 2017 and projected to June 2022), which included data related to the impact of COVID 19 pandemics on coffee and pig meat prices and the reduction of farm tourism.

Figure 4 (a) shows that there are no differences in coffee sales and revenues between scenarios because the other sources of income do not affect coffee harvest. The behavior of coffee sales agrees with the two coffee flowerings that arise in Colombia each year, one from April to June and the most important from October to December. Furthermore, producers’ revenues from coffee bean sales depend on coffee international prices and production costs. Accordingly, these revenues might sometimes be very low, and they may be even negative in some periods, generating losses for the producer. (Figure 4 (b))

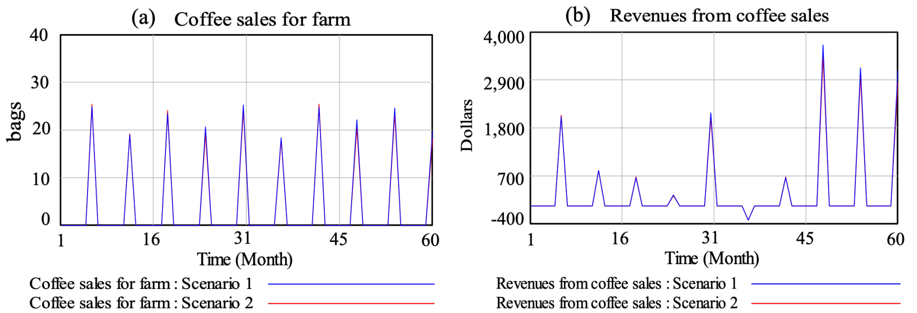

Fig. 4. Simulation of coffee bean sales by farm and its associated profitability

Figures 5 (a), (b) and (c) illustrate that the additional revenue from other sources may be comparable to the coffee bean revenue. The additional income from farm tourism increases in the summer when more tourists come to the farm. Figure 5 (a) reveals a significant reduction of visitors to the farm beginning in month 33 (March 2020) due to the mandatory quarantine caused by the COVID 19 pandemics.

Figure 5 (b) shows some peak production periods of beekeeping products due to the flowering of coffee plants. Each year, a honeycomb generates on average 35 kg of honey and 12 kg of pollen, and the model was run using a typical measure of 1.3 hectares per farm, which corresponds to the area of 82 percent of the coffee farms in Colombia (FNC 2018). In addition, the maximum allowed number of honeycombs per hectare is two. As a result, the simulation indicates that the revenue from this activity is not significant.

Figure 5 (d) compares the different revenues. The average monthly revenue from coffee bean sales equals \$232 while the average monthly revenue from other income sources equals \$153, producing a total monthly average revenue of \$385. Although this figure exceeds the minimum monthly wage in Colombia (approximately \$252), it can be not enough for the average coffee producer's family group of around 4 people.

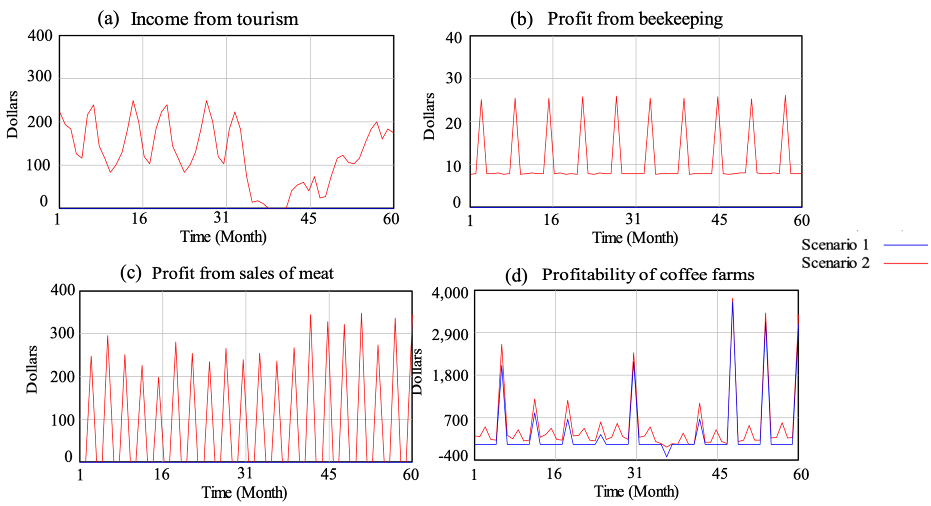

Fig. 5. Behavior of coffee farms with additional sources of income

Finally, Figures 6 (a) and (b) compare the generation of methane from pig feces in Scenario 2 with and without using a biodigester to produce biogas. It is important to note that the investment on the biodigester was amortized over the analyzed time horizon. A significant reduction in emissions of methane to the atmosphere is shown.

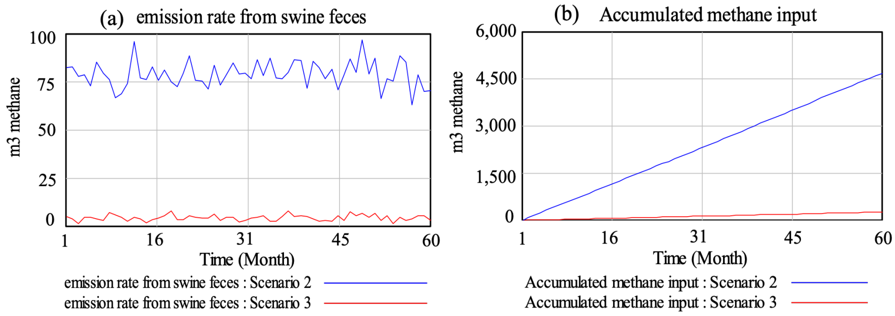

Fig. 6. Methane emissions with and without biofuel generation

6 Conclusions

The study of the sustainable coffee supply chain that considers economic, social, and environmental elements by means of systems dynamics is a topic that deserves more research. As a case in point, several problems have been identified in the coffee supply chain in Colombia, such as the uncertainty in international prices, the small profitability proportion received by coffee growers, and their lack of generational replacement.

To reduce the effects of these factors and improve the coffee supply chain sustainability, we propose system dynamics influence and Forrester diagrams that consider the following improvement alternatives: the permanence of farmers in the field encouraged by better technologies; the production of high-quality beans; and the creation of diverse income sources such as beekeeping, farm tourism, and small-scale animal raising.

According to the influence diagram, these alternatives produce at least six reinforcement loops that could contribute to the economic, social, and environmental sustainability of the coffee supply chain in Colombia. Preliminary runs of the model show that the revenues from other sources different from coffee bean sales may be significant. Besides, the model can be useful to analyze the environmental implications of some production activities such as pig raising and some social impacts of the COVID 19 pandemics, for example, on tourism reduction. Our ongoing research will analyze additional sustainability aspects of selected coffee farms in the region of Valle del Cauca, Colombia.

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