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System Dynamics Application as a Tool to Evaluate Soil Improvement Strategies in Colombia's Sugarcane Cultivation

Dayhanna Stephania Vargas-Mesa[1], Juan Carlos Osorio-Gómez[1],
Patricia Torres-Lozada[1], Luz Karime Torres-Lozada[2]

[1]Universidad del Valle,
Colombia

[2]Fundación Universitaria Unisangil,
Colombia

{dayhanna.vargas, juan.osorio, patricia.torres}
@correounivalle.edu.co,ltorres2@unisangil.edu.co

Abstract. Sugarcane cultivation is one of the main crops in Valle del Cauca, Colombia. However, intensive agricultural production leads to soil depletion (which in the long run can seriously affect production) and therefore the economic development of the region and the country. In this study, it was proposed to evaluate through the system dynamics methodology, the possible long-term impacts that this crop could generate in the Valle del Cauca's soils. The simulation's model was applied using Vensim DSS software and it explored soil recovery scenarios using compost, which is produced from sugarcane residues composting (cachaça and bagasse). It was evident that the utilization of this by-product can represent an important contribution in the soil's loss and degradation reduction, plus economic and environmental benefits.

Keywords: Systems dynamics, land use, sugarcane.

1 Introduction

Over the past 50 years, agricultural technology advances and increased demand due to population's growth, have raised the soil's pressure. In many countries, intensive agricultural production has led to soil depletion, threatening the productivity of soils and the ability to meet the needs of future generations [1]. Colombian's agriculture is diversified, and traditional crops continue to occupy the largest proportion of the sowed area, highlighting those used as a raw material in the production of Colombian's most consumed foods.

This is the case of sugarcane, which has approximately sown 352,786 for 2019, (from this amount, 200,499 belong to the Valle del Cauca's department) [2, 3]. For this reason, it is necessary to conduct studies that contribute to an adequate management in the producer's side of the supply chain to identify and establish improvements in the production processes, and even more so in developing countries [4, 5].

The excessive use of commercial fertilizers has contributed to reduce the organic matter content (OMC) and different physicochemical soil's properties, resulting in its quality's decrease, acidification, and contamination. [6, 7].

Based on the problems caused by commercial fertilizers, organic compost use has led to a growing worldwide interest in the utilization of organic materials [8, 9], as it has been proved that these can increase soil's fertility and improve physical, chemical and biological properties [10] being a safer and more effective alternative for nutrient recovery [10, 11] and leading to a commercial fertilizer's usage reduction in regard to crop production [12].

An alternative to organic amendment is cultivation and processing by-products that come from sugarcane, such as cachaça and cane bagasse [13, 14]. Due to its high impact in the country, and even more in the Valle del Cauca's department (where there is a suitable cropping area of approximately 400,618) [15], this study assessed the applicability of the system's methodology dynamic, which is a modelling approach based on systemic thinking and the usage of feedback and delays information-based perspective.

This can be used to understand the dynamics of complex behavior on physical, biological, and social systems [16, 17]. In this study, the impact of applying compost (which results from cachaça's and cane bagasse's composting) over the cultivation of sugarcane, was evaluated over a period of 40 years using tools from system dynamics.

2 Methodology

The study was applied to the context of sugarcane cultivation in Valle del Cauca's department, Colombia. A diagram of Influences was drawn up and based on this a Forrester diagram was proposed to design two hypothetical scenarios for a period of 40 years. From 2001 to 2041, the scenarios have the following characteristics:

Scenario 1 - Sugarcane cultivation with compost application: The compost application rate varies according to the type of soil, crop, and season. The World Health Organization (WHO) states that 100-300 Ton/Ha of compost is usually required per year [18].

This study assumed a requirement of 300 Ton/Ha compost from the cachaça's and bagasse's composting by-products, whose processing time is in the order of 90 days [14, 19]. In addition, a percentage of soil loss due to compaction was considered.

This is the most evident factor in the sugarcane production process due to the agricultural work generated by the agricultural machinery [20], which was 1% [21, 22].

Scenario 2 - Sugar cane cultivation without compost application: it is evaluated without the use of compost. In this case, a soil degradation rate of 0.004 is proposed [23, 24]. In both cases, it is assumed that the productions reported by the different sugarcane entities are based on traditional fertilization, which is made of chemical fertilizers.

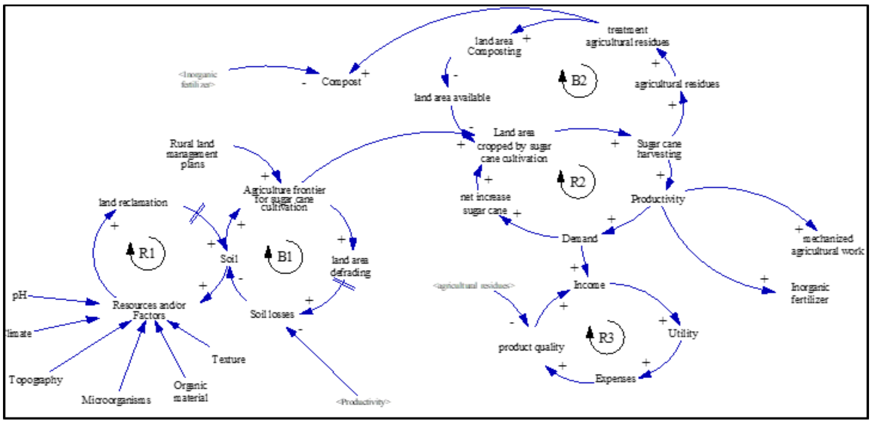

Fig. 1. Sugarcane cultivation influence diagram.

3 Results

3.1 Diagram of Influences

Figure 1 shows the relationship of the feedback loops, whether positive or negative, of the different variables involved in the appropriate land use for crop production (specifically for sugarcane). Each positive feedback or reinforcement loop (R1, R2 and R3) is described below and is understood as the variation of a propagating variable, reinforcing the initial variation, and tending to generate both growth behavior and negative feedback or compensation (B1 y B2).These indicate that the variation of a variable determines what counteracts the initial transition and tends to generate equilibrium behavior [25, 26].

Positive feedback or reinforcement loops are:

R1: represents that within greater availability of Resources (pH, climate, Topography, microorganism, organic matter, and texture), there is greater soil recovery, leading to more soil availability over time (with the conditions for use in agricultural activities) [1, 27].

R2: represents that the greater the sugarcane cultivation's area sown, the greater the yield will be, which leads to an increase in productivity. This will be bound to the product's increased demand, resulting in a rising effect on the cane net's increase [3,28].

R3: demonstrates that higher incomes with the cultivation of sugarcane, lead to the generation of greater profits, being one of the most representatives and with the greatest contribution of Gross Domestic Product in the agricultural sector. Therefore, the sugar sector has implemented improvement strategies and processes investments, which in turn have improved the crop's productivity and the product's quality [14, 19, 29].

Negative feedback loops, or compensation ones are:

B1: shows that the higher the land use, the more degradation problems will arise, leading to gradual losses of soil and making the resource less available, with soil's over-use or overexploitation. Land and soil degradation refer to the negative decrease or alteration of one or more ecosystem's offerings and environmental goods, services and/or functions. This is caused by natural or man-made processes which, in critical cases, may cause the loss or destruction of the environmental component [30].

B2: shows the relationship between the use of organic waste and the area available after the soils are recovered. The more waste is used as compost for organic waste, the more can be returned as fertilizer, conditioner, or supplement for fertilization. As a result, the physical, chemical, and biological properties improve, leading to a more environmental alternative, reducing costs at the level of fertilization, and minimizing the impact generated by soil degradation) [31].

3.2 Forrester's Diagram

Figure 2 shows the basic variables that give the movement to the system and are indicated as "Level", which were taken to perform the simulation associated with the production of sugarcane cultivation and its relationship to the use of land suitable for the development of such crops:

- Sugarcane planting is associated with factors such as cultivation area, preparation time of the soil and the area that is destined for the agricultural vocation. In addition, the area of soil degraded by the compaction factor was considered, which is associated with the demand of the crop and its harvest (see Fig.2A).
- For the sugarcane's production and harvesting process, the response is given to the demand's satisfaction and production's sales (see Fig.2B).
- The use of organic wastes in the sugarcane's production involves the generation of wastes from the process of composting that will be used in the soil for their improvement and up to their processing (see Fig.2C).
- Some variables associated with the income and expenses that are considered in the sugarcane's production process, were considered for the profit flow (see Fig.2D).

Now, the result of the two evaluated scenarios will be presented: where A represents the income-to-expenses ratio discharges, B shows the relationship between the costs of inorganic fertilizers and those produced by the resulting composting process, C shows the correspondence between the area to be cultivated and the sown area, and D shows the generation's residues behavior and how the compost is consumed when it is used as organic fertilization.

- **Scenario 1** - Sugarcane cultivation with compost application

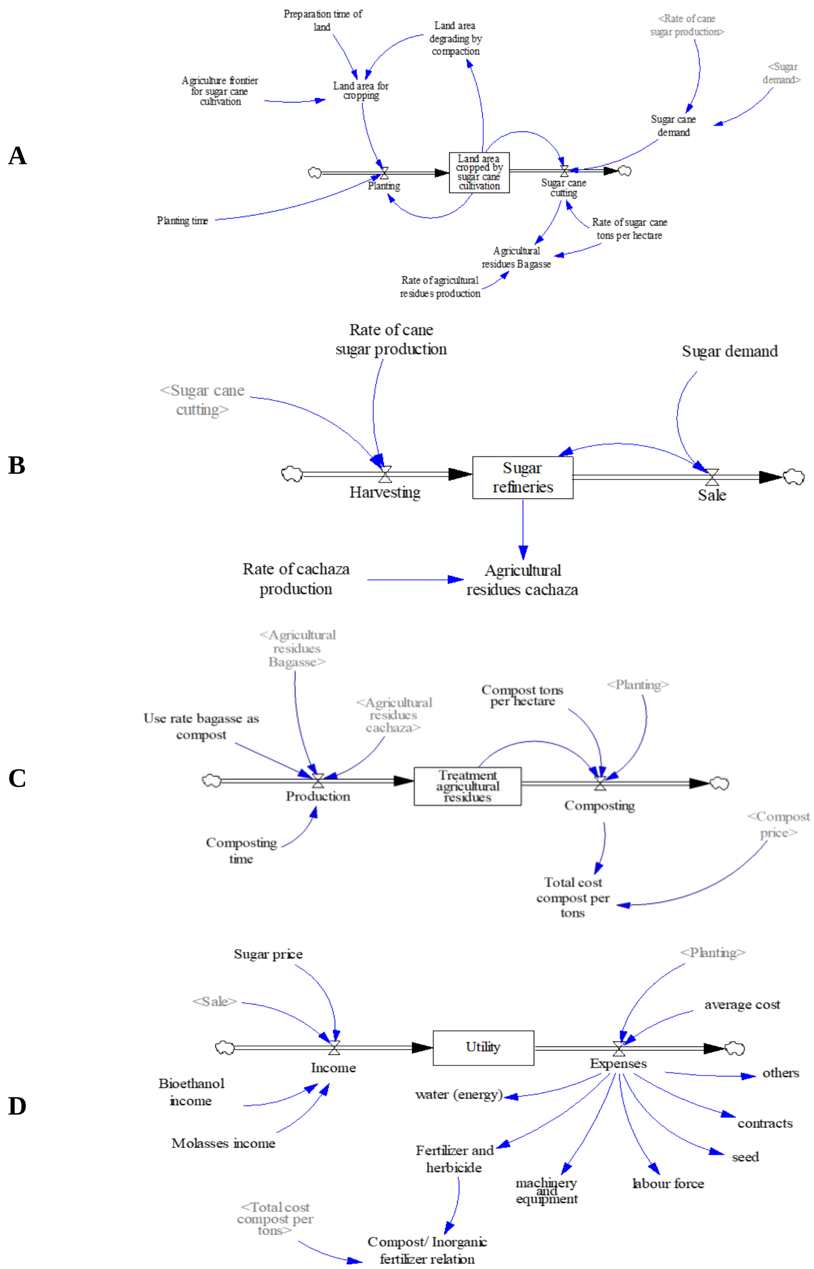

Fig. 2. Resulting Forrester diagram for cane cultivation.

Figure 3 shows the result stated in scenario 1 for the Forrester diagram in sugarcane cultivation.

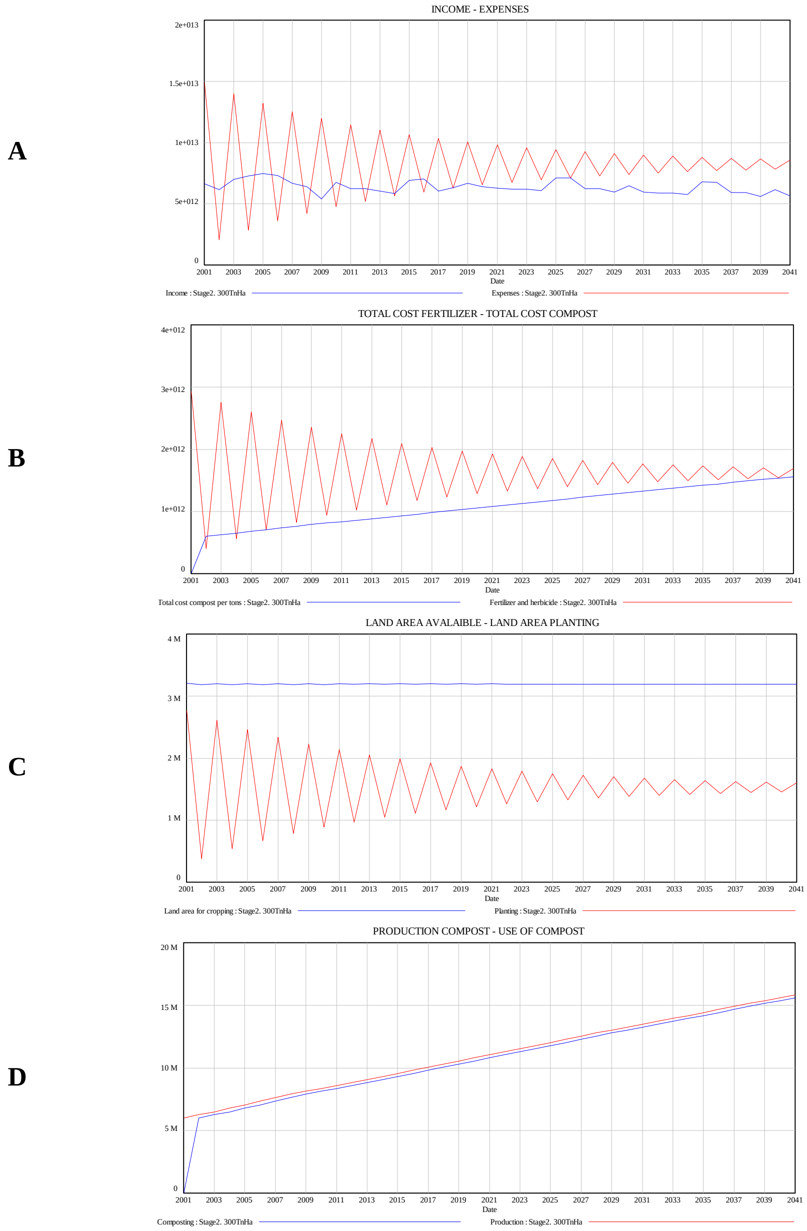

Fig. 3. Scenario 1 - Forrester diagram in sugarcane crop.

– **Scenario 2 -** Sugarcane cultivation without compost application

Figure 4 shows the outcome of the proposed approach for Scenario's 2 outcome.

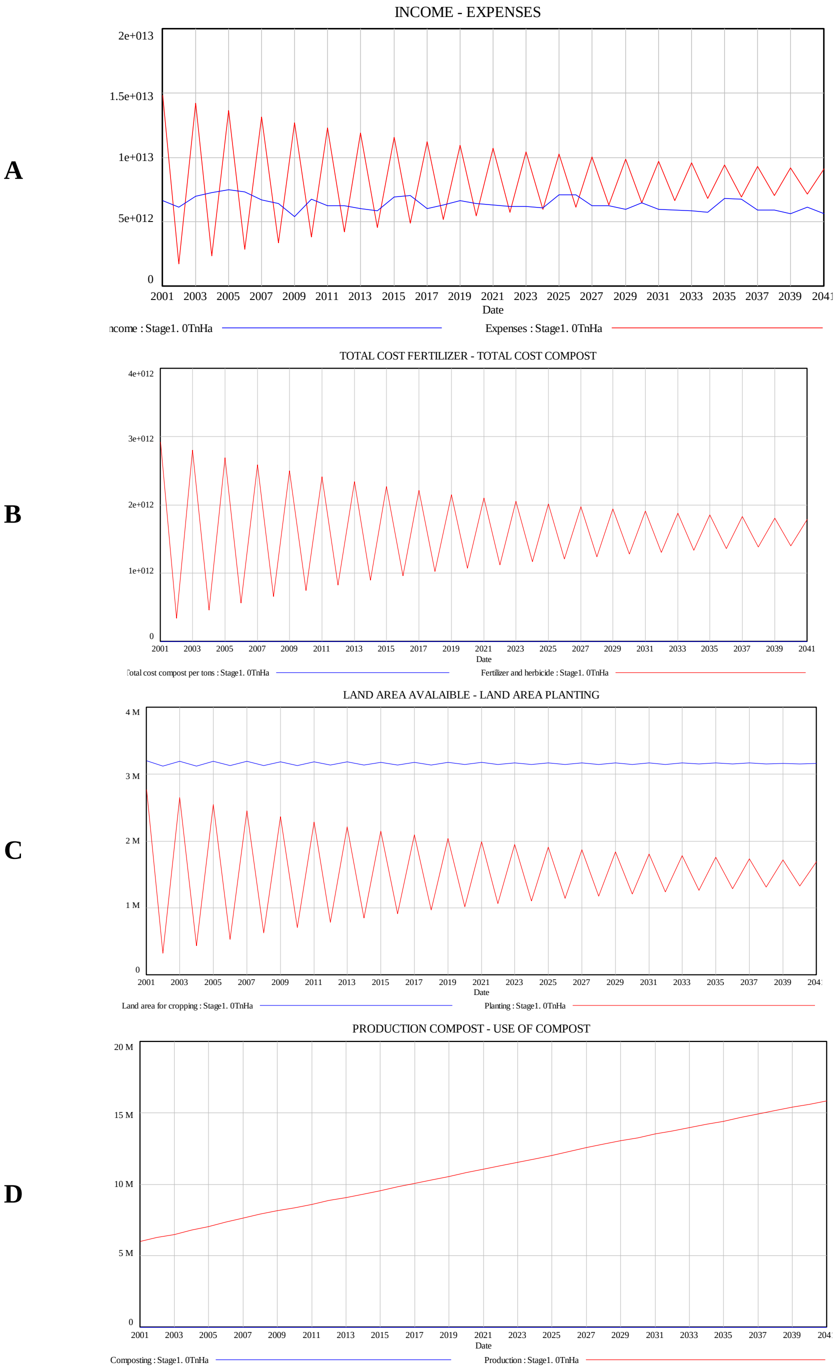

Fig. 4. Scenario 2 - Forrester diagram in sugarcane crop.

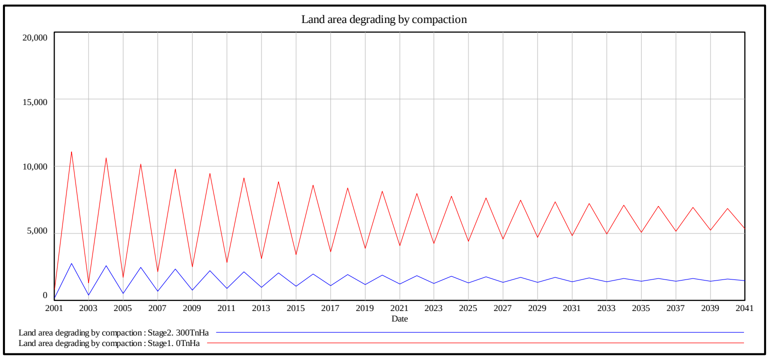

Fig. 5. Approach of soil's degraded area by compaction for both scenarios.

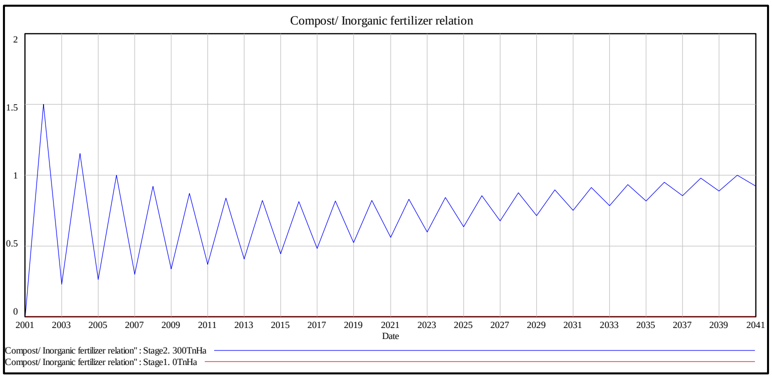

Fig. 6. Approach on the compost/fertilizer cost ratio over the sown area.

When comparing the two scenarios, it can be shown that a positive impact is generated by making use of the by-product resulting from the organic's composting waste generated in the sugarcane's cultivation. By compaction, there is a soil degradation reduction and, as well, it favorably affects the economic aspect since the cost associated with the use of compost is lower than the costs incurred for inorganic fertilization. We also observe the close relationship between the generation and consumption of compost within the process, which means that all the compost generated can be used in soil recovery tasks through organic fertilization.

Figure 5 shows the influence of the organic waste's usage on the soil's degradation variable by compaction. For this case, with a crop such as sugarcane it is evidenced that the use of compost from the cachaça's and bagasse's composting contributes to the mitigation of the gradual's degradation impact in the 40-year observation window over land use.

Figure 6 shows that the cost of composting ranges from 0.3 to 1.5 (percentage of the compost's cost proportion vs the fertilizers and herbicides cost), indicating that its cost is of greater benefit than inorganic fertilizers. Additionally, the area to be sown meets the demand's requirements and leads to costs reduction assumed by inorganic fertilization.

In a review of related topics, it was evident that there are no similar studies focused on the use of soil associated with the organic waste's usage versus production and improvement of costs compared to the production processes of sugarcane cultivation. Nevertheless, certain studies were found, such as the application of system dynamics in the evaluation of the Bioethanol Production Potential from Panel-Cane: dynamics between contamination, food safety and land studies [24]. In this study, the Colombian's panel-cane was characterized for producing agro-fuels in Colombia and it evaluated the influence of oil's price in sugar and panel.

Another case study found is The Systemic Approach to Sustainability in Bioethanol Production, which interconnected the production's process indicators to qualitatively highlight the main attributes of the system [25].

4 Conclusions

The utilization of the cachaça's and bagasse's composting by-product resulting from the sugarcane production process may contribute greatly to reducing the soil's loss and degradation (currently occurring in the world due to extensive cultivation practices such as that of sugarcane in Colombia).

The incurred costs to carry out the composting process can be recovered gradually over time, since carrying out the soil's restoration process with the same by-products leads to the fertilizer's investments cost reduction. In addition, it was evident that the generated waste was consumed entirely in the process, which means that there is no loss of the obtained composting. According to the requirements established by the crop, the compost generated would be entirely consumed and would not meet the needs of the crop, so the use of compost is more a complement than a replacement for chemical fertilization.

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