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Dynamic modeling of the CO_2 emissions behavior by fossil fuel combustion during the land sequence preparation and pre-harvest activities in a sugar cane crop

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Modelación dinámica del comportamiento de las emisiones de CO_2 por combustión fósil durante la preparación de suelos y levante de un cultivo de caña de azúcar

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Abstract
This paper presents the results of a study pursuing the evaluation of the CO_2 emissions behavior by fossil fuel combustion from the agricultural equipment used during the land sequence preparation and pre-harvest activities in a sugarcane crop corresponding to a sugar mill of the Valle del Cauca state, as a local study case. A simulation model from the system dynamics point of view was developed as a research methodology. The main results reveal that the land sequence preparation activities represent 73% of the total CO_2 emissions in respect of the pre-harvest activities considered in this study, like the fertilization and the weed control. Through some sensitivity analyses by considering a complete conversion from commercial to organic area for the next 25 years, it is not possible to observe significant changes in the cumulative levels of CO_2 emissions (decrease of 2.3%). However, changing the land sequence preparation from "conventional" to "light 3", these emissions reduced up to 22.65%. Thus, we obtained a carbon footprint of 70,103.8 t of CO_2-eq and a level of cost savings of 64% compared to the diesel fuel. Finally, this research shows that the adoption of specific agricultural practices by agro-ecological zones represents an opportunity to reduce the long-term CO_2 emissions.

Keywords: *CO_2 emissions, dynamic modeling, fossil combustion, sugarcane crop.*

Resumen
Este artículo presenta los resultados de un estudio que consistió en evaluar el comportamiento de las emisiones de CO_2 por combustión fósil de la maquinaria agrícola utilizada durante las labores de preparación de suelos y levante de un cultivo de caña de azúcar correspondiente a un ingenio azucarero del departamento de Valle del Cauca, como caso de estudio a nivel local. Como metodología de investigación se desarrolló un modelo de simulación desde un enfoque de dinámica de sistemas. Los principales resultados revelan que las labores mecánicas de preparación de suelos representan un 73% de las emisiones totales de CO_2 con respecto a las labores mecánicas de levante de cultivo consideradas en este estudio, como son fertilización y control de malezas. Por medio de los análisis de sensibilidad desarrollados, al considerar una conversión total del área comercial a orgánica para los próximos 25 años, no se observan cambios significativos en el nivel de emisiones acumuladas de CO_2 (reducción de 2,3%). Sin embargo, al cambiar el tipo de preparación de suelo de Convencional 1 a Liviana 3, éste se reduce en un 22,65%, obteniendo así una huella de carbono de 70103,8 t de CO_2-eq y un nivel de ahorro económico del 64% con respecto a consumo de combustible Diesel. Finalmente, esta investigación muestra que la adopción de prácticas agrícolas específicas por zona agroecológica representa una oportunidad de reducción de emisiones de CO_2 en el largo plazo.

Palabras Clave: *Combustión fósil, cultivo de caña de azúcar, emisiones de CO_2, modelación dinámica.*

1. Introduction

Between the years 1970 and 2004, the world emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFC), perfluorocarbons (PFC), and sulfur hexafluoride (SF_6) —measured by its global warming potential— increased in 70% (24% between 1990 and 2004), passing from 28.7 to 49 gigatons of equivalent carbon dioxide ($GtCO_2eq$). Specifically, the CO_2 emissions increased around 80% (28% between 1990 and 2004), which represented 77% of the anthropogenic Greenhouse Gas (GHG) emissions in 2004 (Barker et al., 2007). In the 2000-2004 National Inventory of GHG of Colombia, the CO2 emissions reached up to 56.6% of the total part of all the GHG due to the burning of fossil fuels (IDEAM, 2009)

The SI-ES scenarios (Special Inform about Emissions Scenarios of the IPCC) project an increase of the basic world emissions of GHG in the 2000-2030 period, passing from 25% to 90%. Likewise, it is projected that the fossil fuels will keep its dominant position in the global set of energies, with an increase in the global emissions from 40% to 110% in the same period. During the land sequence preparation and pre-harvest of the sugarcane, several types of tractors can be used per labor to execute. The CO_2 emissions level depends on the power of the engine and its associate cylinder capacity, on the fuel consumption rate —related with the labor execution time—, and on the number of "walks" required given the type of soil preparation (conventional/traditional, soft, and zero), which differs of the pre-harvesting cycle where the sugarcane is (ratoon or sett) and on the agro-ecologic zone where the lot is present.

Given the global problematic that the agro-industrial sector represents for the environment and the lack of previous studies regarding the projection of CO_2 emissions generated by fossil fuels combustion of the machinery employed in the land sequence preparation and pre-harvest processes of the sugarcane (López et al., 2014); we identified the opportunity to develop a research focused on the evaluation of the behavior of these emissions in a 25 years projection. This, by using a simulation model from the scope of the system dynamics, which was applied to a sugar mill of the studied area. Punctually, the simulation model (Zeigler et al., 2000) was based on the population/demographic dynamic theory under the scope of the descriptive research —either analytic or explicative—, given the dynamic modelling process (Ford, 1999; Forrester, 1961; Sterman, 2000). Its structure was developed using the Vensim® PLE software, and the equations that fed the model were obtained from the theoretical calculations established by the Intergovernmental Panel on Climate Change (IPCC) in 2006, specifically in the third chapter related with mobile combustion (Waldron et al., 2006).

This type of dynamic models is widely used in several approaches (economical, political, social, biological, the ones related with health, quality systems and the environment, among others). For this case, these models represent a considerable utility in the projection of some carbon footprint scenarios in the short, medium, and large terms; they also allow to evidence a behavior pattern of the GHG emissions in several scenarios. This will allow the companies the establishment of GHG reduction plans in different time instants, by constantly assess the impact of their man-made activities in a simulation context, without direct intervention in the study field.

Through a posterior and quantitative scenarios evaluation and the behavior of the obtained emissions through the sensitivity analysis, we were able to conclude that the CO_2 emissions generated by the fossil fuel combustion of the agricultural machinery employed in the land sequence preparation and pre-harvest processes of the sugarcane crop *do not* depend on neither the type of the crop nor the fraction of the commercial area that starts its process from commercial to organic. Conversely, these emissions are mainly affected by the type of soil preparation. The act of knowing —in a systematic way— several scenarios of the behavior of the GHG emissions, and the adoption of more adequate farming methods to prepare the soil and pre-harvest the crop given the agro-ecologic zone, allow a meaningful reduction of CO_2 emissions in the long term. This, without affecting the efficiency of the productive processes and the system productivity in general contribute to the sustainability of the sugar sector.

2. Methodology

2.1 Description of the conditions for the simulation model

The *Valle del Cauca* state has about 225,560 hectares of sowed sugarcane, where an approximate of 25% (56,400) are proper of the sugar mills, the 75% remaining is from more than 2000 independent cultivators (Asocaña, 2012). However, regarding the soil preparation, 49% of the area is prepared by the sugar mills and the remaining 51% by the independent cultivators. For the calculation of the carbon footprint in the studied area, we considered the average number of hectares sowed in one of the main sugar mills.

On the other hand, we projected the behavior of the CO_2 emissions in the long term from the combustion of the diesel fuel used by the agricultural machinery. The modeling was developed over an annual base with a simulation period of 25 years, which considers the average projection time of the global GHG emissions worldwide. Additionally, given the fact that the renewal period of the sugarcane in the *Valle del Cauca* state is, on average, each 5 cuts, we determined the generated emissions during the preparation of one soil in renovation —i.e., ratoons in the cut 0—. Afterwards, we obtained the emissions coming from the preparation of a soil type sett (from the first to the fifth cut). That is, each 5 years, a cycle of ratoon and 4 cycles of sett must be taken in a 5-year period.

Equally, we defined —as a basis— a fraction of 5% of pass from the commercial to the organic area and we calculated the total CO_2 emissions coming from the soils preparation and the pre-harvesting of the sugarcane, given the adequate hectares of commercial handlings, in transition, and organic. Consequently, we calculated the potential emissions of these crops in a 25-year period.

Finally, in order to prepare the soil in the ratoon type seed cycle, the definition of the pre-harvesting process to use must be defined; this by following the requirements of the crop, classified as “conventional 1”, “conventional 2”, “conventional 3”, “light 1”, “light 2”, and “light 3”. Alternatively, to prepare the soil in the sett type seed cycle, we used a combination of labors that require a lower number of “walks” regarding this types of farming. Also, to perform an adequate soil rising, some mechanized labors are used to apply fertilizers to the crop (vinasse, compost, synthetic fertilizers, organic matter, green fertilizers), and application of herbicides for weed control. Citing information gathered by means of visits performed to the studied sugar mill, 88.7% of the hectares are prepared with “conventional 1”, 4.4% with “conventional 2”, and the remaining 6.9% with “light 1”. The initial model was simulated taking as a basis the fuel consumption of the agricultural machinery used in the fields, given the more representative preparation type (“conventional 1”) and the mechanized labors of fertilization and weed control during the pre-harvesting process of the sugarcane. Subsequently, we developed some sensitivity analyses by modifying the fraction of the commercial, in transition, and organic areas and the Types of Soil Preparation (TSP) given the agro-ecologic zones of each one of them. Finally, we performed a contrast between the contribution of the emissions from the several types of mechanized farming processes and the ones in the fertilization and weed control processes during the pre-harvesting stage.

2.2 Components of the system

In the following paragraphs, we present —in a detailed manner— the classification of the parameters, levels, flows, and auxiliary variables with the initial values established. Also, we present the equations and definitions of the used units in the model (please refer to Annex A to further information).

Parameters

We established as a fixed value the CO_2 emission factor of the Colombian diesel fuel, its heat of combustion, and its global warming potential. In contrast, the fuel consumption was determined by the number of "walks" the machinery uses given the labor, the execution time of the activity, and the fuel consumption rate per hour. However, this variable was set as an adjustable value that varies given the six TSP proper of the studied sugar mill.

Similarly, we determined some delays as annual interruptions presented in the system to renew a commercial, in transition period, and certified as organic areas. In other words, these delays represent the duration time of a sett, which, when is renewed, receives the name of ratoon. Conversely, given the actual trend of hectares' conversion from commercial to organic in the *Valle del Cauca* state and, punctually, in the studied sugar mill, we defined as a parameter a fraction of the conversion area with an initial value of 5%, as it was described in the previous section.

Level variables

These are state variables used to represent accumulations or de-accumulations in the system through the time. In this case, we established the commercial, transition, and organic areas as level variables. In these areas, we observed a reduction of the hectares of commercial procedures and an increase of the ones receiving clean processes. As initial assumption for this particular case, we established that 75% of the hectares belong to the commercial area, and the 25% remaining correspond to the transition and organic soils. It is important to focus that these percentages are related with the hectares of each type of crop in the studied sugar mill, where a total of 12,000 hectares are present.

Instead, we defined the accumulative CO_2 emissions by fossil fuel combustion of the machinery during the soil preparation and pre-harvesting processes as a level variable that was started to be gathered from an initial value of 0 t of CO_{2e}/year, since no historical data of the CO_2 emissions are found that allowed the establishment of an initial basis for this situation.

Flow variables

These ones are responsible for the variation of the levels per time unit. From this, the levels are affected by the input and output flows in the system. The variables related with the initial amount of the commercial, in transition, and organic areas in the ratoons harvesting cycle are considered; that is, the amount in renovation. Besides, the transition area that, after 3 years is certified as organic, was also considered. Regarding the output flows, we considered the variables related with the amount of these areas in the sett harvesting cycle that finish the 5 estimated cuts before the renovation of the area. Additionally, we considered the total CO_2 emissions by fossil fuel combustion.

Auxiliary variables

This kind of variables eases the understanding and the definition of the flow variables, given their capacity to represent —in themselves— individual concepts in a momentary response time. Some of these variables represented the total CO_2 emissions per ratoon and sett preparation, also mechanical fertilization and weed control labors in the commercial, transition, and organic areas.

Exogenous variables

They represent independent and external processes to the system actions, but with the possibility to affect it. For instance, the climatic and meteorological variables as the rainfall amount, relative moisture, and temperature might affect indirectly the gases concentration in the atmosphere. Nevertheless, for our research, we excluded these exogenous variables since the calculation of the carbon footprint was performed in a theoretical way following the IPCC guides. Consequently, these external observations were not recorded.

2.3 Calculation of the CO_2 emissions by fossil fuel combustion

First of all, the level and flow variables are defined following the Forrester diagrams theory (1961), measured in terms of tons of CO_2eq. From this, we can summarize the following:

The equations that fed the level variables previously mentioned —which allowed the observation of accumulations in an organic level and CO_2 emissions—, were developed following the accumulative structure presented in Equation (1).

$$N(t) = N(0) + \int_0^t (FE - FS)dt \qquad (1)$$

Where:

N = Level; FE = Input Flow; FS = Output Flow

N(t) represents the organic level area or accumulated CO_2 emissions in a "t" time, which corresponds to an initial level of the organic area —CO_2 emissions—, plus the accumulated difference between the input flow and the organic area exit —CO_2 emissions—. This during a pre-established time interval.

On the other hand, the equations that fed the input and output level variables mentioned in the previous section were based in the multiplicative structure that allows, as input variables, the levels, the auxiliary variables, and the constants, as Equation (2) shows.

$$F(t)=TN \times M(t) \times N(t) \qquad (2)$$

Where:

TN = Normal flow (constant); M (t) = Multiplier of the normal flow (auxiliary); N (t) = Level

F(t) represents the input or output flow in the time "t", which equals to the product between the normal flow constant, the multiplier auxiliary variable of the normal flow, and the reached level in the "t" time.

Alternatively, the auxiliary variables equations are related with the theoretical calculation of the CO_2 emissions generated by the fossil fuel combustion, given the proposed methodology by the IPCC in 2006 (Waldron et al., 2006) in its second volume, as Equation (3) presents.

$$CO2\ Emissions = \left[\sum_j \left(Fuel_j \times EF_j \times PC_j\right)\right] \times PCG_{CO2} \qquad (3)$$

Where:

Fuel = Amount of the "j" consumed fuel; EF_j = Emission factor of the "j" fuel; PC_j = Heat of combustion of the "j" fuel; PCG_{CO2} = CO_2 global warming potential.

The CO_2 emissions equal to the sum of the product between the "j" fuel, the corresponding emission factor for that kind of fuel, and its heat of combustion for all the "j" types of fuel, multiplied by the CO_2 global warming potential.

From here, we developed the theoretical calculation of the CO_2 emissions by considering, not only the fuel consumption per ratoon/sett preparation and weed control, but also the emission factor of the Colombian diesel established by the Mining-Energetic Planning Unit (UPME, *Unidad de Planeación Minero-Energética*) and by the used agricultural machinery in the studied sugar mill. Besides, the heat of combustion of that fuel and the CO_2 global warming potential were also considered.

3. Results and discussion

3.1 Base simulation

On one hand, we obtained three initial simulation scenarios that present the total CO_2 emissions given the mechanized labors of soil preparation and pre-harvesting in a commercial, in transition, and organic sugarcane crop. We considered a simulation period of 25 years and an initial supposition that the fraction of conversion from commercial to organic is 5%. Hence, the total commercial area is reduced to 22% and the transition area increased to 78%, increasing the total organic area to 139% (See Figure 1).

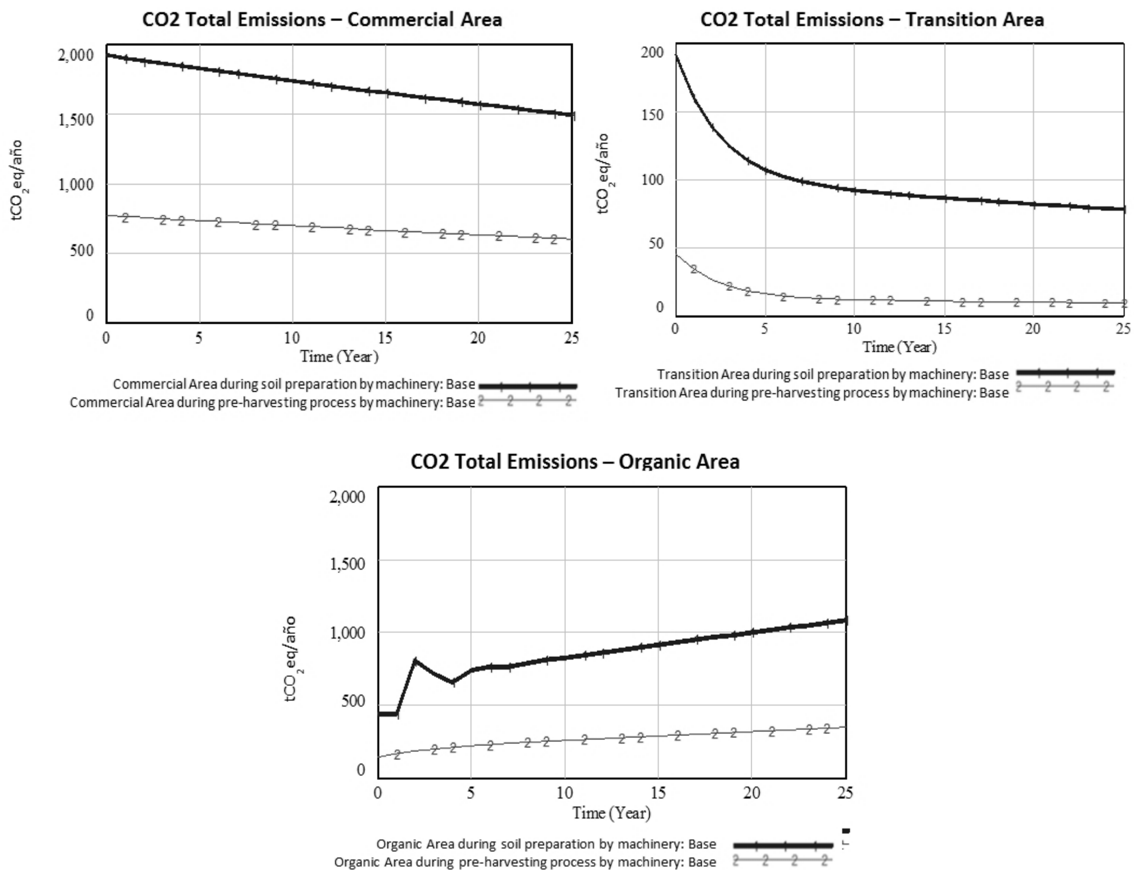

Figure 1. *Total CO_2 emissions given the type of area (tCO_2eq/year).*

Given the simulated behavior of the CO_2 presented in Figure 1, we observed that the mechanized labors of soil preparation represent a significant contribution to the carbon footprint, compared to the mechanized labors used for the pre-harvesting process (i.e. fertilization and weed control). For a 25-years simulation time and, given the conditions previously mentioned, the CO_2 emissions by fossil fuel combustion during the soil preparation process reached up to 66,385 tCO_2eq.

Likewise, the pre-harvesting process emissions reached up to 24,252 tCO_2eq, which represented an inferior value of the emissions in, approximately, 63% regarding the soil preparation labors.

Given the representability in the carbon footprint from the mechanical labors required to prepare the soil —in a detailed level and given the TSP commonly used in the studied sugar mill—, we obtained that the accumulative CO_2 emissions generated during the soil preparation in the pre-harvest of ratoons, exceeded the generated emissions during the soil preparation that received, at least, one cut. This is, in the sett cultivation process, the emissions were surpassed in 82%, 38%, and 92% corresponding to a commercial, a transition, and an organic crop, respectively. These results are obtained —on average— after the fifth cut of the sugarcane, where a higher number of labors to renew the soil and sow new seeds are required.

3.2 Model validation

Given the importance of the decisions taken from the models simulation, it is important to validate if the model provides an adequate representation of the real system. This validation must be performed both at a structure and behavior levels. Firstly, an evaluation of the structure towards qualitative evaluations of relations between variables based on a verified knowledge of the modeled system is required. Secondly, the veracity of the behavior is assessed in an indirect way, towards the application of behavior tests to the patterns generated by the model.

In the following paragraphs, we present a simulated proof of behavior proposed by Sterman (2000), known as *Sensitivity Analysis*. This consist on the modification of the fixed initial values in the parameters of the model and examine the results due to this change. In our study case, we developed two sensitivity analyses by modifying the Fraction of the Commercial area that turns to Organic (FCO) and the TSPs in the ratoons' pre-harvest process, this since they represent a broader contribution to the CO_2 emissions compared to the sett type.

3.2.1 Changes in the fraction of the organic area

The first scenario consisted in the determination of the possibility to obtain a relevant reduction in the GHG emissions at a long term (25 years) during the transition of a crop from commercial to organic. From here, the first sensitivity analysis presented the total and accumulative CO_2 emissions generated during the soil preparation and pre-harvesting processes of a sugarcane crop, given the fraction of the base organic area of 5% and the modification of this parameter in a 10% and 100% (Table 1).

Table 1. *Total CO_2 emissions given the changes in the FCO.*

TOTAL CO_2 EMISSIONS BY FOSSIL FUEL COMBUSTION	BASE (FAO5%)		FAO10%		FAO100%	
Area type	**Year 0 (t of CO_2-e/year)**	**Year 25 (t of CO_2-e /year)**	**Year 0 (t of CO_2-e /year)**	**Year 25 (t of CO_2-e /year)**	**Year 0 (t of CO_2-e /year)**	**Year 25 (t of CO_2-e /year)**
Commercial Area	2695.39	2096.53	2630.1	1587.17	1454.86	5.4963
Area in Transition	236.783	87.919	302.075	138.256	1477.32	13.5947
Organic Area	587.432	1430.82	587.432	1869.85	587.432	3508.34
Total emissions	3519.605	3615.269	3519.607	3595.276	3519.612	3527.431
Accumulative emissions	0	90636.6	0	90308.7	0	88552.6

Firstly, when an increase of 5% in the fraction of the commercial area that starts the transition process towards organic (i.e., given a FCO of 10%), the accumulative emissions level only reduced 0.36% and, under the hypothesis that, if a transition of the 100% of the commercial area to organic in the assessed period, this would result in a reduction of the 2.3% in the accumulative CO_2 emissions.

Given the increase of the FCO did not result in relevant changes in the accumulative CO_2 emissions, we concluded that the emissions generated by the fossil fuel combustion of the agricultural machinery do not depend on the type of area where the soil is prepared and the sugarcane is pre-harvested. Consequently, a low level of sensitivity is present.

Given the previous fact, we decided to perform another sensitivity analysis, where we modified the sequence of soil preparation labors, since its relevant contribution to the CO_2 emissions (73%) over the pre-harvesting processes. This is described in the following section.

3.2.2 Change in the type of soil preparation

During the preparation of a new lot in a soil in renewal process (ratoon), higher amounts of CO_2

were generated to the atmosphere respect to the setts preparation. This, since a higher number of labors and "walks" per labor, a higher execution time of the activities, and a higher fuel consumption rate. For this reason, the second sustainability analysis was focused on the assessment of the contribution to the total emissions from the different combinations of mechanized labors used in the studied mill. Likewise, we assessed the contribution of the most adequate farming processes given the agro-ecologic zones with greater representability. In this case, these zones correspond to the 6H1 and 11H1.

Table 2 presents the changes in the total CO_2 emissions when a modification in the most used soil preparation process is presented (i.e., "conventional 1"). This table also presents the assessment of the other five farming sequences. It is important to focus that we considered an assessment of the CO_2 emissions for all the six types of soil preparation processes defined by the studied sugar mill. This, considering the total amount of hectares (12,000) and without differencing the agro-ecologic zones.

Table 2. *Total CO2 emissions given the changes in the TSP.*

Types of soil preparation	Total number of walks	Execution time of the TSP (hr/(ha*walk))	Fuel consumption (t/ha)	Total CO_2 emissions Year 0 (tCO_2eq/year)	Total CO_2 emissions Year 25 (tCO_2-e/year)	Accumulative CO_2 emissions (tCO_2eq)
Conventional 1 (Base)	8	4.32	0.23	3519.61	3615.28	90636.6
Conventional 2	7	4.32	0.22	3450.22	3540.2	88770
Conventional 3	6	3.57	0.21	3380.82	3465.12	86903.3
Soft 1	6	4.62	0.16	3033.87	3089.75	77570.3
Soft 2	6	3.12	0.13	2825.69	2864.52	71970.4
Soft 3	5	2.67	0.12	2756.3	2789.44	70103.8

Under the initial hypothesis that 88.7% of the prepared hectares are with the "conventional 1" TSP, the accumulative CO_2 emissions in a 25-year period can reach a value of 90,636.6 tCO_2eq. However, if these hectares are prepared with "conventional 2", a reduction of just 2.06% is obtained (1866.6 tCO_2eq/year) in the accumulative CO_2 emissions level during the assessed period. If "light 1" is applied, a considerable reduction of the emissions is reached, the exact value is 14.42% (13066.3 tCO_2eq/year). Despite that the three TSP previously mentioned refer to the sequences commonly used in the studied sugar mill, when we evaluated the six as a whole one, we found that the farming process "light 3" produces the higher reduction of these emissions, reaching up to 22.65% (20532.8 tCO_2eq/year). Within this last case, we obtained the lower level of the carbon footprint (i.e., 70103.8 tCO_2eq). Besides, the adoption of this farming process can enhance economical savings up to 64% regarding the fuel consumption, equivalent to $ 6,000,000 COP (Colombian Pesos) (i.e. U$ 2,000) per prepared hectare.

Given the fact that the 100% of the hectares cannot receive only one type of soil preparation, it is necessary to consider the features of the same to obtain the most adequate farming type. This allows the gathering of an efficient fuel consumption and, consequently, the reduction of the CO_2 emissions towards the atmosphere. For this reason, we decided to assess the required farming methods for the most representative agro-ecological zones, as 6H1 and 11H1. These zones correspond to 36% (4,320 ha) and 34% (4,080 ha) respectively, of the total hectares belonging to the studied sugar mill.

The Agro-Ecologic Zone (AEZ) 6H1 belongs to a group of soils with fine, dry, and deep texture that it is easily cracked with a normal moisture. It is the first of the nine large Groups of Soil Preparation (GSP) (Quintero et al., 2008). Given the practices for the soil preparation recommended for these groups, we deduced that for this AEZ, the sequence of labors "light 1" should be used. In this sequence, the plough with disks and rakes in adequate humidity conditions do not allow the soil to compact; plus, the correct subsoiling allows the ventilation conditions (Carbonell et al., 2011). From this, the pass from "conventional 1" towards "light 1" in this AEZ entails a reduction of 4,704.2 tCO_2eq (corresponding to 14%) and savings in the economical topic up to 23% ($2,137,800 COP/ha, U$700/ha).

Similarly, the AEZ 11H1 corresponds to a group of soils with sharp fine texture, dry, deep, well drained, and with a normal group of moisture. The GRT of *Cenicaña* classifies it as the GSP 4. Consequently, the use of the "light 3" sequence is recommended, since the subsoiling for the preparation and pre-harvesting of the setts is not justified (Carbonell et al., 2011). This TSP can enhance an optimum development of the crop, without the admission of re-processes in the area. Consequently, the pass from "conventional 1" to "light 3" generates a considerable reduction of the CO_2 emissions up to 23%, i.e., 6,981.7 tCO_2eq, and in the economic topic, savings up to 64% ($6,000,000 COP/ha, U$2,000/ha).

In the types of soil preparation previously analyzed, the light farming contributes to the soil conservation by easing the accumulation of humidity within it and generating protection against the erosion. Conversely, the conventional farming can affect the fertility of the soil and generate higher amounts of GHG to the atmosphere, given the considerable amount of labors and "walks" performed in comparison with the light farming. For this reason, the obtaining of a relevant source of reduction/mitigation of GHG emissions to the atmosphere can be reached if the agricultural practices are performed in an efficient way and following the requirements of each particular soil. This might increase the sustainability of the sugar sector in the long term.

Citing some studies developed worldwide regarding the simulation scenarios of GHG, in 2030, the total amount of GHG emitted to the atmosphere might be 63 $GtCO_2eq$. This value might be reached if strict mitigation policies are not performed and only a minimal support for the adaptation of the climate change to the most vulnerable regions is provided (Guyatt et al., 2012). Therefore, the knowledge in a systemic way of the several scenarios —in the long term— of this issue that, nowadays, covers not only the agro-industrial sector, but also a whole system of complex interactions between climatic, environmental, economic, politic, institutional, social, and technological processes; allows the preparation of a response to the climate change. With this response, it is expected that an effective decision-making process regarding risk conditions is considered to propose alternatives that allow the reduction of the irreversible effects caused by the growing emissions of GHG to the atmosphere.

4. Conclusions

We were able to conclude that the mechanical activities of soil preparation generate a contribution of 73% in the total CO_2 emissions compared to the mechanical labors of pre-harvest considered (i.e., fertilization and weed control). Given the higher representativeness in the emissions from the soil preparation labors, we developed some sensitivity analyses that allowed to conclude that the generated emissions from the fossil fuel combustion of the agricultural machinery do not depend neither on the type of the crop nor of the fraction of the commercial area starting its transition towards organic. Nonetheless, these emissions are affected by the chosen type of soil preparation, characterized by the number of "walks" and the applied fuel consumption rate during the time of the labor. From here, we noted that under the lightest type of soil preparation, a considerable reduction of the total CO_2 emissions is achievable, corresponding to 23%, plus a maximum economical saving of 64% in the executed labors in the field.

Regarding the presented model that allows the assessment of the behavior of the CO_2 emissions by fossil fuel combustion, we propose to develop a model based on the experimental calculations of the emissions that considers exogenous climatic and meteorological variables as a future basis for the present research project. Besides, it should consider the incidence in the emissions level coming from another factors as the direction and speed of the wind and the near presence of another machinery during the sampling processes in the field. Also, the assessment of the trends in terms of combustion in engines in the following 25 years is desired. Equally, we recommend to determine the behavior of the gas flow of the CO_2 emissions considering, not only the emission sources, but also the absorption of the gases coming from the sugarcane. Finally, the consideration of the emissions generated during the transport of the materials to the different rows is also an important variable to look after.

Contrariwise, in order to obtain a behavior of the emissions coming from the following phase in the pre-harvesting process, we propose a simulation model to assess the incidence of the application of different fertilizers rates (both synthetic and organic). Mainly, we recommend to evaluate the contribution of the CO_2 emissions by decomposition of urea and the N_2O emissions by vinasse and compost decomposition; both in commercial, transition, and organic crops. These values should be compared with the emissions of the managed soils by decomposition of the remaining agro-chemical products. Hence, the development of comparative sensitivity analyses between the GHG emissions generated by the decomposition of the fertilizers and the mechanized labors of soil preparation and pre-harvesting stages of the crop might be developed. Besides, the definition of enhancement opportunities regarding with the reduction of the emissions of the main GHG gases without affect the productive processes and the efficiency of the system should be a *must-have*.

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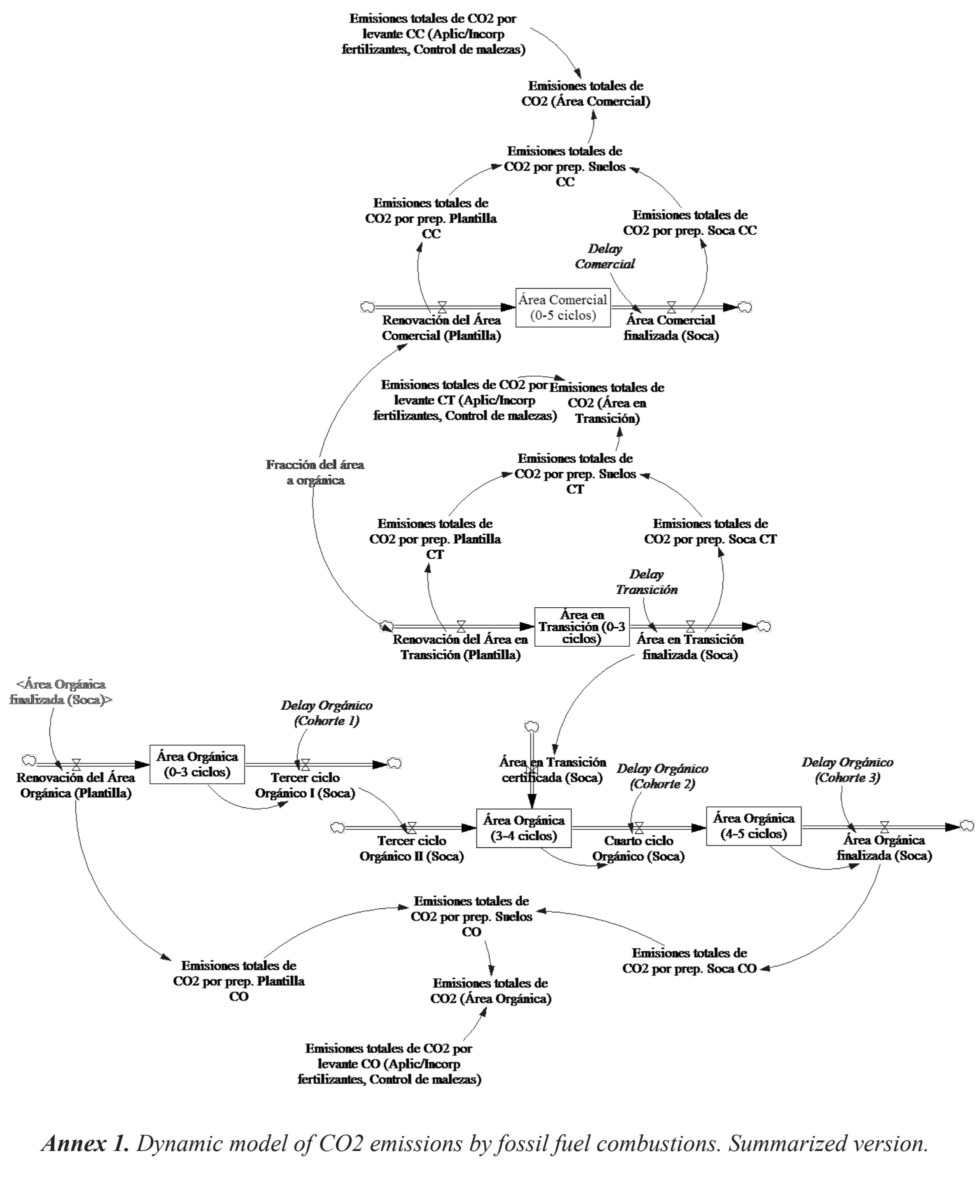
Annex

I. Model of system dynamics by fossil fuel combustion



Annex 1. *Dynamic model of CO2 emissions by fossil fuel combustions. Summarized version.*