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Sustainability assessment to support governmental biodiesel policy in Colombia: A system dynamics model

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ABSTRACT

Combustion of fossil fuels in the transport sector represents the second largest source of greenhouse gas emissions. For this reason, governments are fostering diversification of energy sources by creating a set of governmental environmental policies and initiatives. In this context, biofuels are expected to represent a substantial part of source diversification, but it is necessary to assess the sustainability of their market to explore its effect on economical, technological, social, political and environmental dimensions. This research presents a dynamic simulation modelling of the Colombian biodiesel market and analyzes the policy support instruments for creating and managing it. A system dynamics based model is proposed to enable decision-makers to understand the influences between the different variables that describe the system and the impact of the biodiesel government policy in Colombia. The primary focus of this paper is to establish the characteristics of each sustainability dimension for the case of study and apply the system dynamics methodology with different types of validation. Finally, the Colombian market status and a sensitivity analysis are developed. The results show that in order to support the development of this sector, it is necessary to diversify the raw materials for the production of biodiesel in the medium term, which means raw materials without competence for the primary rainforest or competition with food productive lands.

1. Introduction

Global carbon dioxide (CO_2) emissions from fossil fuel combustion and from industrial processes increased in 2013 to the new record of 35.3 billion tons (Gt) of CO_2, which is 0.7 Gt higher than last year's record (Olivier et al., 2014). For reasons such as this, countries are fostering energy source diversification by creating a set of governmental environmental strategies and deploying incentives for increased utilization of energy from renewable sources (European Parliament, 2009; Congresso Nacional Brazil, 2014). Among the energy renewable sources, biofuels have attracted interest as an alternative to petroleum (US EPA, 2013). Renewable biofuels include four categories: *total renewable fuels*, *advanced biofuels, cellulosic and agricultural waste-based biofuels* and *biomass-based biodiesel (BBD).*

Among the industrially available biofuels, worldwide biodiesel production has shown exponential growth in the period 2003 to 2013, rising from 0.321 (Mb/d) to 33.4 (Mb/d) (EIA, 2014). The growth of the emerging biodiesel market offers opportunities for economic and social development for countries of emergent economies such as Colombia (MinMinas et al., 2008). Colombia presents the conditions to develop the biodiesel market due to its favorable geographical and climatic conditions for oil palm cultivation (Consorcio CUE, 2012). In this context, Colombia has developed laws and mandates defining the legal framework for the use of biofuels (Law 693, 2001; Law 939, 2004), with the aim of diversifying agricultural production, increasing energy security, and promoting employment and regional development, specifically in rural areas (MinMinas et al., 2008).

Estimating the impact of the national energy policy is a complex task because it needs the consideration of different dimensions to

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evaluate local sustainability. The traditional sustainability assessment approach called the Triple Bottom Line (TBL) has been widely used to consider environmental, social and economic dimensions (Lee et al., 2012; Govindan et al., 2013; Ahi and Searcy, 2015). A recent study (Bautista et al. 2016) proposed a framework to enlarge these dimensions to political and technological dimensions.

In order to quantify and model scenarios, Systems Dynamics has been used in multiple research works (de Wit et al., 2010; Chang et al., 2013; Wang et al., 2014; Barisa et al., 2015). Its use is justified because that methodology allows the decision-maker to identify the different components of a complex system and review the probable consequences of his decisions (American Society for Cybernetics, 2014). However, to our knowledge, the studies based on system dynamics to understand the biodiesel market do not consider simultaneously the entire five sustainability dimensions. Additionally, the existing models do not explain precisely the processes of data collection or the selection of mathematical relationships between different variables, to allow the reproduction of their work and the simulation of new policies before implementing it.

This article presents a dynamic simulation modelling of the Colombian biodiesel market and analyzes the policy support instruments for creating and managing it. A system dynamics based model is proposed to enable decision-makers to understand the influences between the different variables and the impact of the biodiesel government policy in Colombia. The primary focus is to establish the characteristics of each sustainability dimension for the case of study and apply the system dynamics methodology with different types of validation.

2. Background information

2.1. Colombian biodiesel market

BBD can be produced from vegetable oils, used cooking oils and animal fats (MinAgricultura, 2014). Oil palm is the source of vegetable oil that has the highest productivity (around 4 tons per hectare per year) (FAO, 2008), which makes palm oil biodiesel more competitive in comparison with other biodiesels. According to the Colombian government, the growth of the international biofuel market offers opportunities for economic and social development, by diversifying agricultural production, increasing energy security, technological development and innovation, and promoting employment and regional development, specifically in rural areas (MinMinas et al., 2008). To foster biodiesel production, the Colombian government has promoted laws and a political framework where tax exemptions and subsidies were established as well as mandates to blend diesel and biodiesel (Law 693, 2001; Law 788, 2002; Law 939, 2004). Consequently, Colombia is the fourth largest palm oil producer in the world (Fedepalma, 2012) and the country has the potential to boost biodiesel production for the local market (MinMinas and UPME, 2010).

2.2. Sustainability framework

Bioenergy systems are complex and have an impact on various levels of nature and society, involving many stakeholders (Buytaert et al., 2011). The study of bioenergy systems should be implemented from a holistic perspective, to provide an integral (quantitative and qualitative) vision about the impact of production on sustainable development (Hacking and Guthrie, 2008). This means that at least three dimensions – environmental integrity, economic resilience and social well-being – must be measured (Lee et al., 2012; Govindan et al., 2013; Ahi and Searcy, 2015). Likewise, Bautista et al. (2016) considered important the analysis of the technological and political dimensions in addition to this classic analysis.

The inclusion of the political issues makes it possible to analyze the manner in which policy directly controls the biodiesel market, such as renewable fuel standards and mandatory blending, increasing the demand for biodiesel, which generates the growth of biodiesel processors, increasing the demand for cultivation land for raw materials, changes in the ownership of land, impact on rural employment and changes in the quality of life and living conditions of communities associated with the biodiesel production chain (Schade and Wiesenthal, 2011; Bautista et al. 2016).

The consideration of the technological dimension could help to answer questions about how new technologies could change the use of first generation biofuels in the future, if it will have a positive impact on social and environmental dimensions (Bautista et al. 2016). Additionally, the analysis of this dimension, proposed by de Wit et al. (2010) seeks to describe the technological learning curve, based on the experience gained in the operation, and scale independent learning. This approach makes it possible to determine the moment when the production cost reductions stop due to learning or investment of biodiesel production technology.

Thus, the proposed approach in this work will apply to the five dimensions: *Political*, *Environmental*, *Social*, *Economic* and *Technological*, to the analysis of system sustainability in the biodiesel market.

2.2.1. Political dimension

Colombia has developed policies to define the mandatory use of biofuels and promote their production through laws, mandates and resolutions. Law 939 of 2004 supports the creation of the biodiesel market, establishing the following (Law 939, 2004):

- *Biofuels from crop or animal origin, for use in diesel engines, of domestic production destined for blending with diesel fuel will be exempt from global tax to ACPM.*
- *Biodiesel will not pay taxes for diesel (25% of the retail price).*

Likewise, resolutions promulgated by the Ministry of Mines and Energy of Colombia, for example 9-1664 (MinMinas, 2012), establish the percentage of mixture to be used in different regions of the country. Thereby, the mixture rate is an external variable, which allows diversifying the energy sources and forcing biodiesel local demand, thus generating the biofuel market in Colombia. Also, other resolutions establish the quality of biodiesel for blending with diesel, or ACPM as is called in Colombia (MinAmbiente and MinMinas, 2014). The biodiesel price structure is determined by the Ministry of Mines and Energy of Colombia, which publishes monthly resolutions of prices (MinMinas, 2014). Taking highest of the following three values: 7179.88 Colombian $ per gallon, updated each year from 1 January 2010; the domestic price of palm oil calculated according to the methodology of Price Stabilization Fund for Palm Kernel, Palm Oil and its fractions; and the reference price of diesel in the international market (UPME, 2014). Except for a few months in 2008, when they were historically high international prices of oil and its derivatives, which has prevailed for calculating biodiesel Producer Income has been the domestic price of palm oil (UPME, 2014).

2.2.2. Economic dimension

Different authors (Oviedo et al., 2010; Marchetti, 2011; Yazan et al., 2011; Zhang et al., 2011) highlight three key aspects that globally have influence on the economic sustainability of palm biodiesel: the price of vegetable oils and its relation to crude oil prices, the relationship between biodiesel demand and production capacity and growth of production of advanced biodiesel.

According to economic theories, the relationship between the price of palm oil and the price of oil is due to the presence of free market competition, because rising oil prices become attractive substitute consumption, there is increment of demand for raw materials (Fontaine, 2000). The same theory explains that palm oil producers will observe the increase in demand and price, like incentives for increasing their production levels, affecting the price of palm oil to reach equilibrium in the market. As for the relationship between biodiesel demand and production capacity, biodiesel production in Colombia satisfied about 85.5% of demand in 2012, so there is a percentage of unmet demand for domestic production (Fedebiocombustibles, 2014; SIGP, 2014).

2.2.3. Social dimension

Growing concern about food security in Colombia is mainly due to rising food prices, which are simultaneously biodiesel feedstock. Based on the Fedepalma report about palm oil sales, Fig. 1 shows the Colombian consumption of palm oil for biodiesel production and other uses. These other uses include use as cooking oil, special fats, cocoa butter substitutes and animal fats, margarines, toiletries, soaps, detergents, cosmetics, toothpastes, candles, lubricants and paints (Garcés and Cuéllar, 1996). It is noted that sales for biodiesel have increased 60% in the period 2008–2013, although the oil sold for other uses has diminished to 30% of the total palm oil sold. Likewise, there is concern about land destination because its use could change from agricultural, food and livestock production to biodiesel feedstock production.

2.2.4. Environmental dimension

Palm oil is currently used as feedstock for biodiesel production in Colombia. Thus, to determine if the impact of biodiesel production on the environment is positive or not, generation of greenhouse gases and the change in land use should be considered (Consorcio CUE, 2012). Depending on the detail level of the model, it will be possible to see direct and indirect land use change.

2.2.5. Technological dimension

The technological development of biodiesel production from palm oil can be quantified using the learning curve (de Wit et al., 2010). An empirical causal relationship that expresses the decline of the cost for each doubling of cumulative number of units (or capacity) produced or installed. This means that production costs are reduced over time by process improvements, experience in the operation and maintenance (de Wit et al., 2010). In addition, there is scale independent learning, because additional reductions can occur through the process of technological improvements, which are not directly related to production.

2.3. System dynamics application in biofuels analysis

System dynamics is a methodology that combines analysis and synthesis, which facilitates the distinction of feedback mechanisms (Forrester, 2013). Between different applications of this methodology, System Dynamics has been recently used by several studies that have analyzed the market for renewable energy sources. For example, Bantz and Deaton (2006) modeled the biodiesel market to understand the reasons for the exponential growth of production capacity of the biodiesel industry in the United States. de Wit et al. (2010) applied and developed the "Biotrans" model in Europe, optimizing costs along the supply chain of biofuels. Oviedo et al. (2010) explained the production and consumption of alternative fuels like biofuels, based on the country's energy security, environmental protection and agricultural development. Oviedo et al. (2011) proposed a system dynamics model representing the behavior and foresight of the biodiesel industry worldwide, considering conflicting points of view about the use of biofuels as an energy alternative to oil. Musango et al. (2011, 2012) implemented system dynamics for assessing biodiesel sustainability in South Africa. Barisa et al. (2015) proposed a system dynamics model for finding the most effective policy strategies on biodiesel in Latvia. Franco et al. (2015) performed an approach from system dynamics to the biofuel market in Colombia.

These studies provide a valuable contribution to policy analysis in the biofuels sector. However, these studies do not consider the entire sustainability dimensions. Nor do these studies explain the data collection and selection of mathematical relationships between different variables. Based on this, this work describes and applies the methodology of dynamic systems, aiming to understand the effect of the policies developed by the Colombian government since 2008, in the different components of the biodiesel market system, including the five sustainability dimensions. In addition, the dynamic model proposed is validated through different statistics criteria.

3. Systems dynamics methodology

The systems dynamic methodology has three general steps: articulation of the problem or conceptualization, dynamic hypothesis formulation, testing and analysis (Bérard, 2010). These steps are divided into activities that allow the decision-maker to understand the process to be followed in order to obtain the quantitative model that represents the target system. This description was based on the work of Lee et al. (2012) and is shown in Fig. 2, adding the activity "Dynamic model validation." Validation must be qualitative and quantitative. In this study, Stella® was used as a platform to conceptualize the biodiesel market in Colombia and to design the dynamic model.

3.1. Methodology description

3.1.1. Stage 1. articulation of the problem and conceptualization

The first step is to analyze the market system sustainability. Each of the five dimensions should be described given the context and conditions for market operation. The description will depend on the country in which the study is conducted. In the second step, the objective is to define the variables representing each of the dimensions and the relations between them. These relationships can be given by theoretical concepts or experience of actors involved in the system. The causal diagram can be construed using these variables and relationships. Finally, the third step is the validation of the causal diagram by asking for the experts' review to verify that the model meets the assumptions of mental maps of those who are related to the system.

3.1.2. Stage 2. dynamic hypothesis formulation

Each variable incorporated in the integrated causal diagram should be represented in the dynamic diagram. This representation is made by different variables. The definition of dynamic variables of the model must start with the investigation of whether they have a pre-established and demonstrated relation, as the known relation production–season. If the relation between the variables is not pre-established, the equation will be obtained from historical data by using least squares algorithms (Draper et al., 1998). Transformations of some variables are made to linearize the set of candidate functions, seeking the best fit with the original curve and the feasibility of the comparison between functions. Validation and selection of the equations is performed using the statistical R^2, R^2 adjusted, p-value, variance analysis and prediction of errors.

The selection process of the equations is as follows:

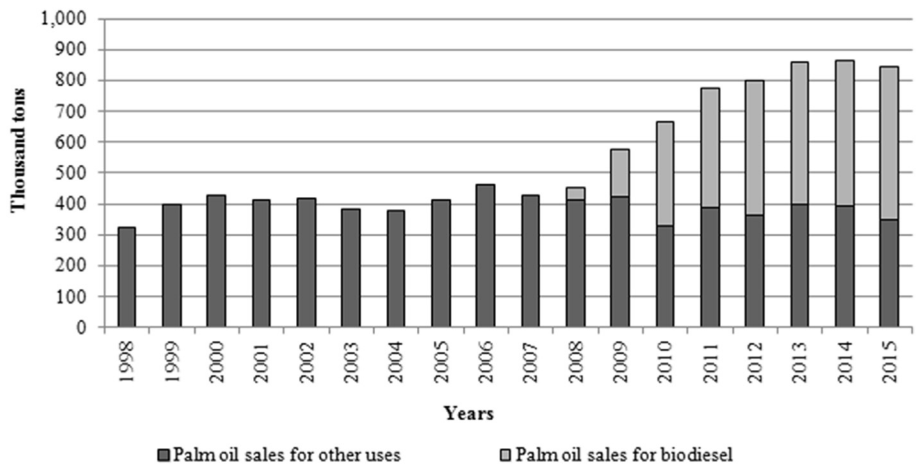

Fig. 1. Palm oil sales in Colombia in the period 2008–2012.

- Perform the regression and get the results for statistical "F-test" from the analysis of variance and compare it with the value of Fisher established (F table [α; $\sqrt{}1$, $\sqrt{}2$]). If:

$$\text{“}F-test\ Analysis\ of\ Variance\text{”} > \text{“}F\ table(\alpha;\sqrt{}_1,\sqrt{}_2)\text{”}$$

$$\alpha = 0,10$$

It agrees that the equation is significant, so it can be used to represent the relationship between the variables. In addition, each variable must be significant ($p-value$) in the equation considering the same approach $\alpha = 0{,}10$.

- The equations that satisfy the constraints of the first criterion should be assessed in the data from which the regression was not performed. Additionally, the forecast errors must be calculated. The relationships that have less error in comparison with the others will be eligible.
- The equation used in the dynamic model is one that complies with the above criteria and has the highest values of R^2 and R^2 adjusted. The value of R^2 adjusted measures the fitness of the equation to the data, but it is necessary to use the criterion of error indicators to measure the predictive ability of a designed model.

Once the equations have been selected, they can be implemented to the dynamic model construction in Stella® for further simulation and validation. It is important to note that the modeler will not know how reasonable the conceptualized diagram is until the model is built and simulated with the selected equations (Albin, 1997). As a consequence, only once the dynamic model is finally completed is it possible to observe whether the model actually represents system reality or some modification must be made to improve their behavior.

For identifying the variables classified as flows, stocks or external variables in the system, it is necessary to determine which variables in the system define their state (their stocks) and which variables define changes in their state (its flows). The variables not included in these two classifications are auxiliary variables (Michael and Robert, 1997).

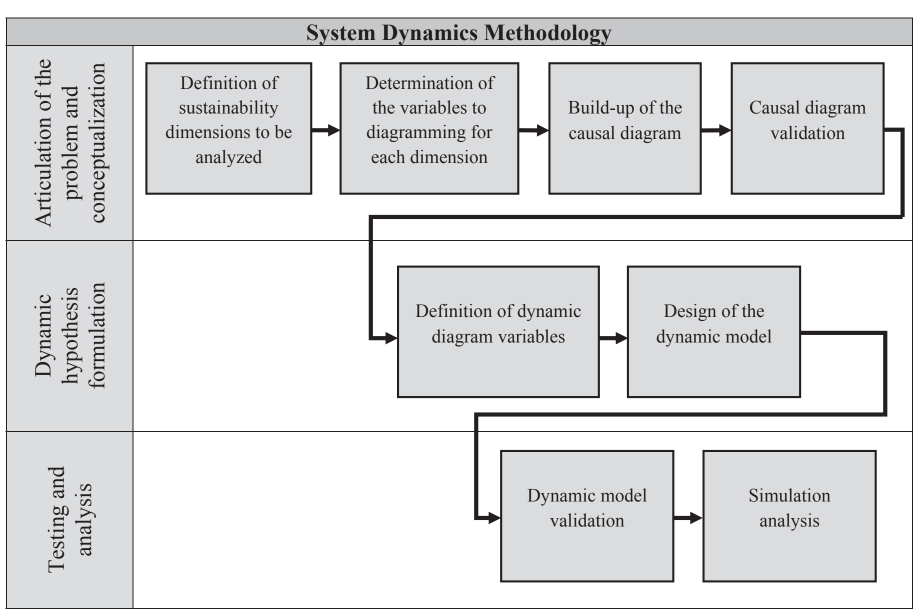

Fig. 2. System dynamics methodology, based on Lee et al. (2012) and Bérard (2010).

3.1.3. Stage 3. testing and analysis

To validate the model and the system the tests described below must be carried out:

- Informal validation: In general, informal criteria resort to expert opinion as a way to assess the quality of the model. This can be done through interviews, panels of experts and the Turing test (Godoy and Bartó, 2002).
- Objective criteria for validation: there are a variety of criteria to objectively validate the result of a system dynamics model (Barlas, 1989). These criteria are:
  - Criteria correspondence between structures: Each model element must have its counterpart in the real world.
  - Criteria correspondence between behaviors: If a model is based on time series representing the evolution of the system, it is possible to establish indicators on the relationship with the behavior that the model predicts. If the initial conditions of the model correspond to the state of the system being modeled, then the behavior of the model should reflect the historical data.
  - Criteria correspondence between phenomena: It is expected that the model can represent both the phenomena observed permanently as exceptional in the real world.

If the model meets these criteria it can be stated that it is valid and may represent the reality of the modeled system. After the validation of the model, it is possible to analyze the forecast delivery of the model and to realize the sensitivity analysis.

4. Application of the system dynamics methodology

4.1. Articulation of the problem and conceptualization

Based on the analysis of the Colombian biodiesel market and taking into account the five sustainability dimensions, the causal diagram in Fig. 3 was constructed. Then, a review and feedback process with experts in the field of the biodiesel industry in Colombia was carried out to validate it.

The causal diagram has four self-regulatory cycles designated by a minus sign in Fig. 3: C_1 represents regulatory policies of biodiesel consumption, C_4 and C_5 represent the palm oil market, supply and demand, and C_3 shows the production regulation based on raw material costs. Furthermore, there are two reinforcing loops, designated by a plus sign in Fig. 3: C_6, which describes decreasing costs through technological development, and C_2, increased production in terms of increased profitability of biodiesel in the market.

The political dimension is represented in cycles C_1 and C_2. In C_1 the resolutions that establish the mixture percentage are represented. And C_2 represents the resolutions that establish the biodiesel price structure.

The economic dimension is represented by the effect of the increment of biodiesel prices on profits, which incentivize the production capacity of enterprises. In parallel is found the glycerol market, which is affected by growth in biodiesel production.

In order to measure the impact of palm oil biodiesel production on the Colombian social dimension, the change in the value of agricultural products will be evaluated. In this study, the effect on the price of palm oil is measured for understanding if there is a risk to food security in Colombia. Fig. 3 shows in cycles C_4 and C_5 that the increased production of biodiesel causes an increase in the palm oil price due to the growing demand. The biodiesel production cost in Colombia is highly dependent on the price of palm oil, and then the rise in the price of palm oil generates a diminution of biodiesel production profitability; therefore, a biodiesel production disincentive is caused. Furthermore, the Colombian government established a set of conditions for the biodiesel market (demand and price), preferential tax conditions, and exemption from taxes, wherewith the biodiesel production profitability is guaranteed.

The environmental dimension is analyzed through the changes in land use, principally the coverture of tropical forest and the changes in agricultural hectares.

The technological dimension is studied by means of the efficient production cost of biodiesel (as shown in Fig. 3, cycle C_6), the production cost diminution linked to technological learning dependent on and independent of biodiesel production.

4.2. Dynamic hypothesis formulation

The dynamic hypothesis formulation is designed according to the integral causal diagram presented in Fig. 3. The formulation of the dynamic hypothesis is developed with the aim of describing the causal diagram through mathematical equations. Initially, the dynamic variables were defined, as well as the mathematical equations that show the relationship between variables. For this purpose, the statistic program Minitab® was used. Afterwards, mathematical equations were validated and finally, the dynamic model was defined through the implementation of the mathematical equations using the Forester Diagrams (stock and flow diagrams) on Stella® software.

The data used to develop the model are quarterly time series between 2008 and 2011. The validation of the mathematical equations was performed, applying statistical criteria that were described in Section 2.1, *Stage 2*. The prediction errors are made by comparing the data for the year 2011.

In the process of Forester Diagram definition, it was necessary to establish sub-models with the objective to clearly show the main relationships that can represent different sustainable dimensions of the biodiesel market system in Colombia. The sub-models are linked to the followings subjects: biodiesel production, biodiesel price and technological development, palm oil production and change of land use. The mathematical equation and the stock and flow diagram for each sub-model will be described below. The variables and the principal equations are shown in Appendix A and B.

- Biodiesel production

The biodiesel production sub-model is shown in Fig. 4, where Biodiesel production (BP_t) as a function of the biodiesel production capacity (BPC_t) and the price of diesel ACPM ($ACPM_t$) in the country and the function is represented by Eq. (1). It is important to clarify that biodiesel production is independent of the price of biodiesel.

$$BP_t = f\{BPC_t, ACPM_t\} \quad (1)$$

The change in biodiesel production capacity ($CBPC_t$) depends on the difference between biodiesel demand and production of the period ($DBBDP_t$), as is shown in Eq. (2).

$$CBPC_t = f\{DBBDP_t\} \quad (2)$$

The stock level of biodiesel (SB_t) depends on production (BP_t) and biodiesel sales (BS_t) and the stock level of biodiesel of the previous period (SB_{t-1}). Glycerol production (GP_t) is calculated from the stoichiometry relation of biodiesel production during the period.

- Biodiesel price and technological development

The sub-model of the biodiesel production cost, price and

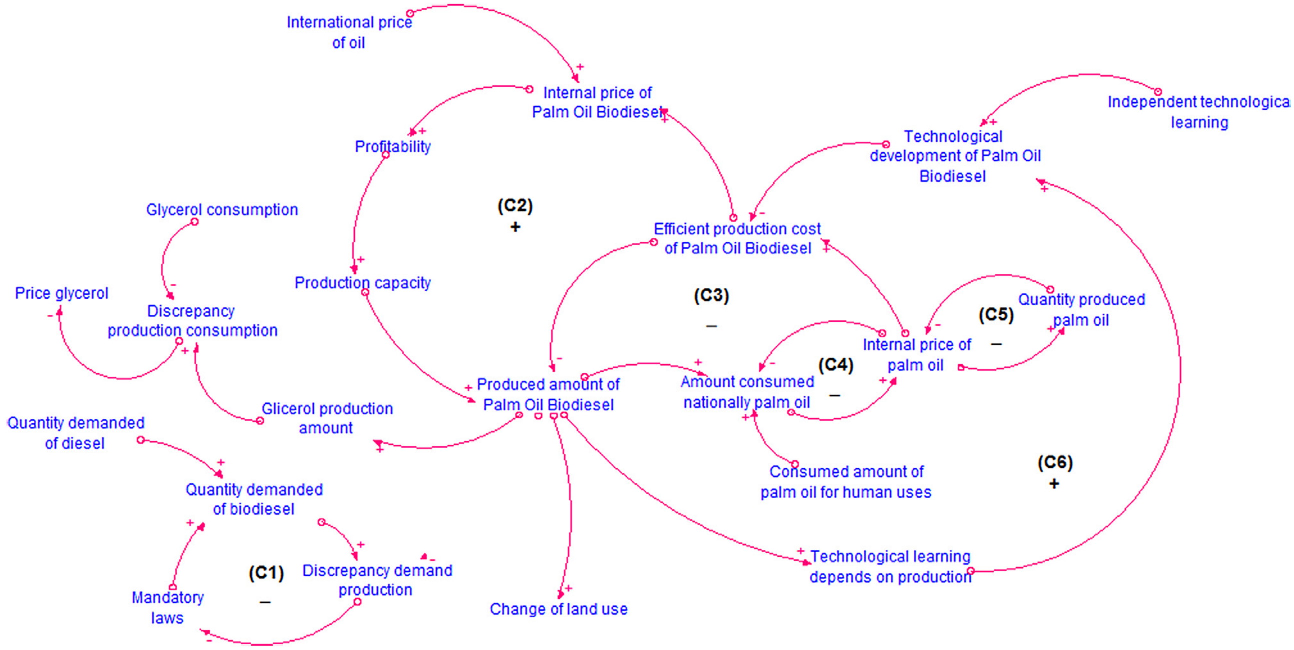

Fig. 3. Integral causal diagrams.

technological development is shown in Fig. 5. The learning curve symbolized by biodiesel production ($LCDBP_t$) is a function of accumulated biodiesel production (ABP_t), represented by Eq. (3).

$$LCDBP_t = f\{ABP_t\} \tag{3}$$

The cost reduction associated with the learning curve independent of biodiesel production, called the technology development curve ($ITDC_t$), is a function of the time and is represented by Eq. (4):

$$ITDC_t = f\{t\} \tag{4}$$

To determine the production costs of biodiesel production ($PCBD_t$), the component associated with raw material cost directly dependent on the price of palm oil ($POPrice_t$) was estimated. Finally, to compare the benefits generated by biodiesel sales (BS_t), the curve of biodiesel price ($BDPrice_t$) was determined, which depends on the biodiesel price from the previous period ($BDPrice_{t-1}$), the value of the ACPM and the palm oil price. These relations give form to Fig. 5, which represents the technological development of biodiesel production from palm oil and its effects on production costs.

- Palm oil production

The Sub-model palm oil production considered palm oil sales, production, price and land cultivated. Palm oil production (POP_t), represented by Eq (6), principally depends first on the season (SI_t), Eq (5), and second on seasonally adjusted palm oil production; the sub-model is shown in Fig. 6.

Palm oil production, represented for Eq (5), depends on palm cultivation; this, in turn, is influenced by seasonal climatic conditions; so a seasonal factor was identified for each quarter of the year. In relation to the factor of seasonally adjusted palm oil production ($SAPOP_t$), this seasonal adjustment depends on the production capacity of palm oil ($PCPO_t$) in the country, the palm oil sales for biodiesel ($POSFB_t$) and the biodiesel price ($BDPrice_t$). Therefore, production (POP_t) finally takes the form of equation (6).

$$SI_t = f\{t\} \tag{5}$$

$$(POP_t) = f\{SI_t, SAPOP_t\} \tag{6}$$

Furthermore, palm oil sales (POS_t) depend on the palm oil price ($POPrice_t$), palm oil production (POP_t) and the amount of palm oil sales for biodiesel ($POSFB_t$), as shown in equation (7).

$$POS_t = f\{POPrice_t, POP_t, POSFB_t\} \tag{7}$$

The variation of palm cultivation in development to production status ($VPHIDTP_t$) depends on the time (t), corresponding to growth of palm hectares in development phase ($PHID_t$), and investments to accelerate production, which are encouraged by the palm oil price ($POPrice_t$), as show in equation (8). The remaining relations of the palm oil sub-model are presented in Fig. 6.

$$VPHIDTP_t = f\left\{t, t^2, PHID_t, POPrice_t\right\} \tag{8}$$

The international oil price WTI (WTI_t) was calculated using the AutoRegressive Integrated Moving Average, ARIMA, because it is a variable in the model which it does not seek to explain, but only represent, as is shown in Fig. 7.

- Change in land use

This sub-model analyzed the relationship between the changes in tropical forest land, the land used for food production called agricultural hectares and farming hectares (lands used for livestock production) and land used for palm cultivation. It was identified that tropical forest land (TH_t) is influenced by the total quantity of hectares intended for palm oil production ($PHIP_t$). Likewise, the agricultural hectares (AH_t) are affected by changes in farming hectares (VHF_t) and the land used for palm cultivation ($TNPH_t$). The sub-model that represents land use change is shows in Fig. 8.

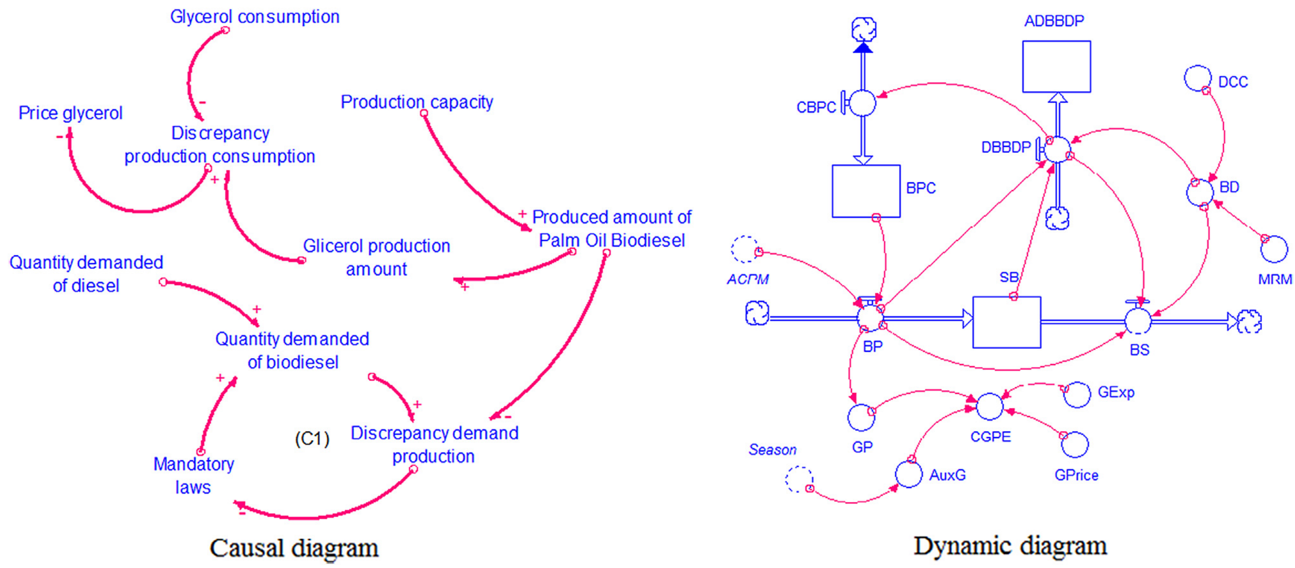

Fig. 4. Sub-model biodiesel production.

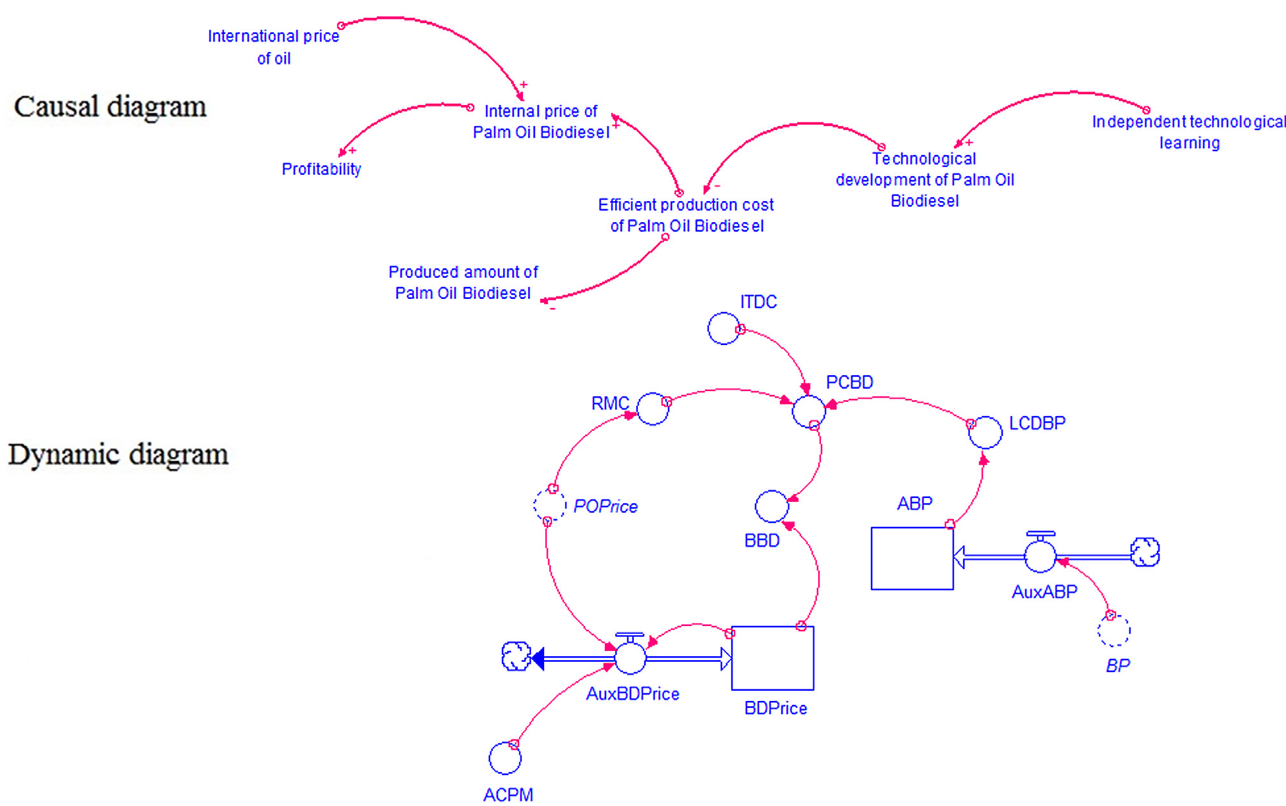

Fig. 5. Sub-model biodiesel price and technological development.

4.3. *Testing and analysis*

In System Dynamics, models go from a vision of structural relationships between the components, through concepts such as positive or negative feedback, to dynamic systems characterized by systems of differential equations (Godoy and Bartó, 2002). So, to validate the model as a representation of the biodiesel market system in Colombia, the criteria described in Section 2, *Stage 3, Testing and analysis,* are evaluated.

To validate the correspondence between structures, the integral causal diagram was defined with the aim that the variables of the biodiesel market system, which are important for researchers, were represented. After the causal diagram has been validated by expert opinion, the dynamic model was established, based on the causal diagram; consequently, the correspondence between structures of the dynamic model proposed in this work has been validated.

The correspondence of behavior and phenomena is measured by the Mean Absolute Percentage Error (MAPE), to calculate the

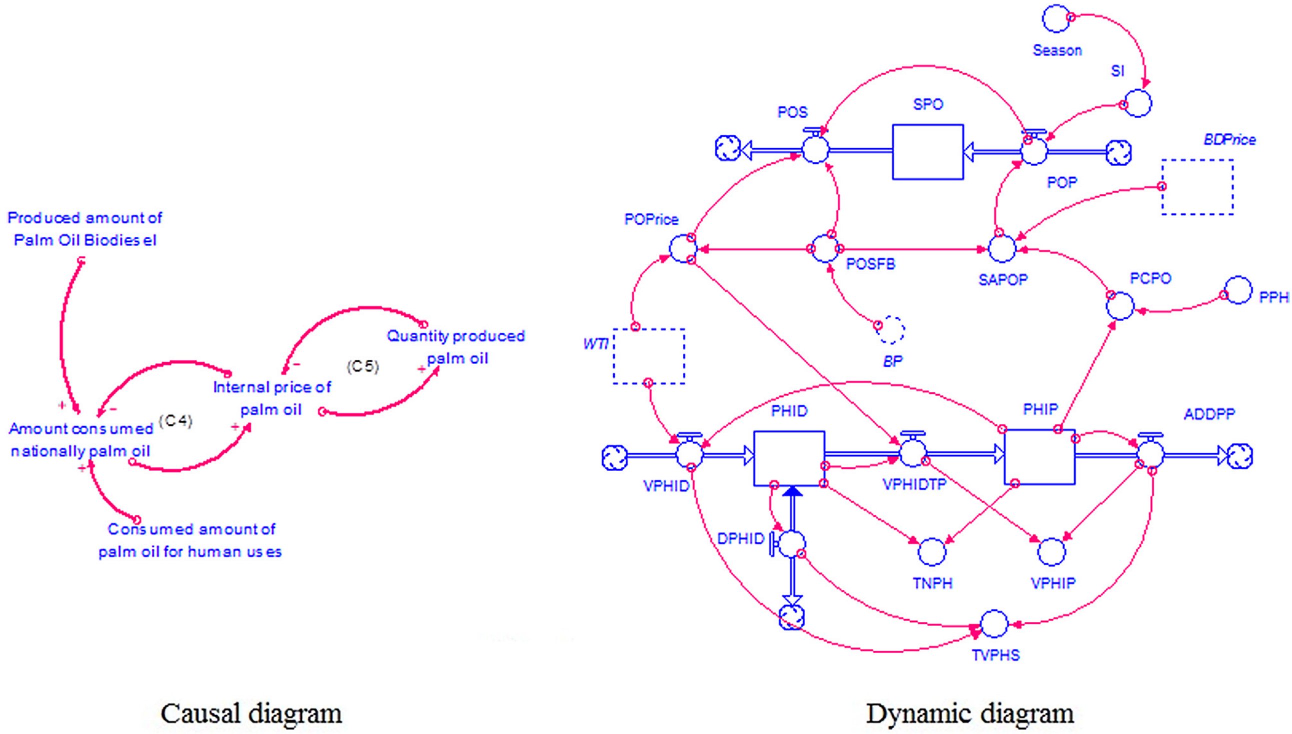

Fig. 6. Sub-model palm oil production.

accuracy of the model, accepting up to 30% error evaluated between 2008 and 2011 (Barlas 1989, 1994). To calculate MAPE, the model was run and the values generated by the model were compared against the collected historical values. The forecast error between 2008 and 2011, of the major variables, is presented in Table 1, where it can be noted that the values are below or at the limit of 30%. According to the MAPE, the causal relationships and equations have been correctly defined, and the model represents adequately the behavior of the biodiesel market in Colombia.

Additionally, it is possible to perform the same procedure to validate the model behavior and representation phenomena using the data for the period 2012 to 2013. As a result, two variables do not meet the validation criteria: the hectares planted with palm and marginal hectares available in Colombia. In the case of hectares of palm cultivation, the model overestimates the expected amount for these years, due to new government policies that have slowed the planting of palm. Then, there is a new external variable that can be included for subsequent studies, the palm oil plantation regulation. Regarding marginal hectares, the model overestimates the number of hectares devoted to the sector, indicating that there are other variables that are affecting these geographic areas and accentuating the problem of replacement land use.

5. Results and discussion

Two types of analysis were established for the components of

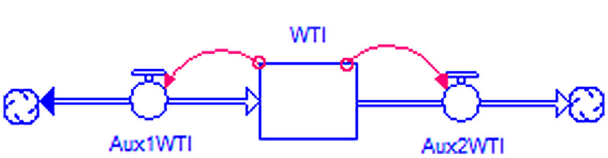

Fig. 7. Oil WTI price.

the biodiesel market system. First, we analyzed what will happen to the system if the pattern of behavior continues over time, without changes in variables, like new resolutions. The second is a sensitivity analysis, to recognize key variables which will affect the system behavior if they are modified.

5.1. Current status of the Colombian biodiesel market

After the validation of the model, a simulation was performed to observe the perspectives of the biodiesel market in Colombia by 2020 based on the current context, without changes in variable structures:

- *Political dimension.*

The forecast that the model provides is that the Colombian government will establish a 15% mandatory blending rate for biodiesel with diesel by 2020.

- *Economic dimension.*

Biodiesel production in Colombia will satisfy the growing demand, increasing from 30.9% of satisfaction in 2008 to 91.3% in 2020. It can be observed that all the biodiesel production is and will be sold, so for the moment there is no biodiesel inventory. The predicted production and demand of biodiesel is shown in Fig. 9.

Fig. 10 shows that the biodiesel price will increase from 1542 USD/t in the year 2008 to 2108 USD/t in 2020, experiencing an increase of 36.7%. This is due mainly to the palm oil price increase, which influences the biodiesel production cost augmentation.

It is clear that the economic benefits of the biodiesel market (*Benefits* = *Biodiesel price*−*Biodiesel production cost*) are not high, showing constant positive values from 2014 and achieving maximum profitability of 10% in 2020. Therefore, it is possible to

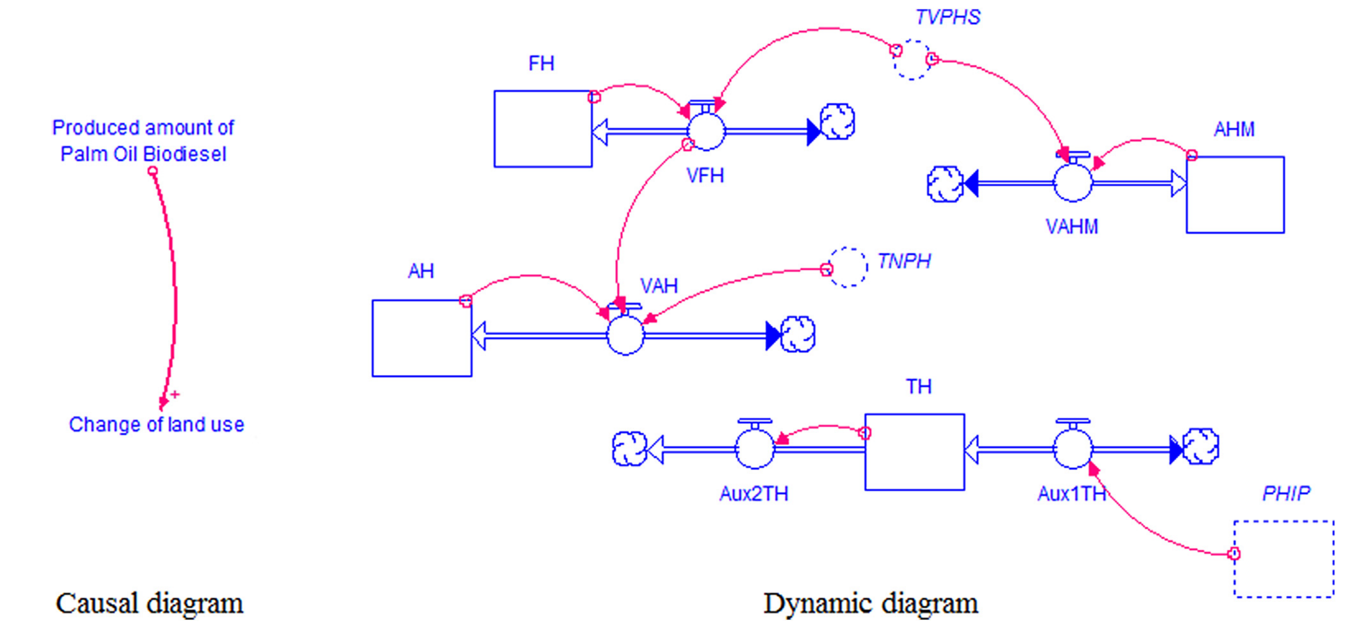

Fig. 8. Sub-model change in land use.

Table 1
Dynamic model validation using MAPE.

Variable	MAPE 2008–2011	Variable	MAPE 2008–2011
Diesel consumption	2%	Tropical hectares	1%
Rate mixture	13%	Biodiesel production capacity	16%
ACPM price	5%	Palm oil total sales	22%
Palm hectares in production phase	1%	Production capacity palm oil	10%
Palm oil price	30%	Biodiesel production	29%
Palm total hectares	3%	WTI price	29%

conclude that the market is not economically viable, unless the government fosters it through subsidies and reductions for taxation, which should be maintained over time.

- *Social dimension.*

Biodiesel market effect on the palm oil price shows an increase of almost 600 USD/t between 2008 and 2020, because the demand for palm oil to be used for biodiesel is not sensitive to price.

The consumption of palm oil dedicated to other uses is affected by the birth of the biodiesel market, because palm oil demand for other uses responds to price, according to the theory of perfect competition market. It can be seen in Fig. 11 that in 2008, 91% of the total palm oil sales corresponded to other uses, including food, while in 2020 it is projected that only 41% of the sales of palm oil will be for other uses.

Given the increase in palm oil price, consumers turn to lower priced supplementary products or restrict their consumption, reducing total palm oil sales for other uses between 2008 and 2017. Subsequently, between 2018 and 2020 consumption increases. This could be due to two reasons: the first is that the value of supplementary products increases, therefore the consumer returns to the main product, and the second cause is the generation of the inelasticity to the price. This means that since it is a product necessary for food and oleo-chemical production, it is necessary to consume it and to transform it without importing the price that it possesses. Ultimately, however, it restricts access to the final product for the low-income population.

- *Environmental dimension.*

Related to the change in land use, shown in Fig. 12, it is observed that the land use for palm cultivation - TNPH presents continuous growth, from less than 0.5 million hectares in 2008 to 1.8 million hectares in 2020. In contrast, land use for agricultural activity - AH in the country presents a considerable decrease by reducing hectares dedicated to this activity, from 3.3 million hectares in 2008 to 157,333 in 2020. More worrying is the reduction in tropical forest hectares - TH, from 59.8 million hectares in 2008 to 47.7 million in 2020; of which 11.3 million hectares are between 2010 and 2020. Concerning farming hectares - FH (land used for livestock production) show only a slight diminution, from 38.8 million hectares in 2008 to 38.3 million hectares in 2020.

A clear relation cannot be seen in the change of the indirect use of land, so it is necessary to conduct a more detailed study regionally in future, considering the geographical distribution of each type of land use and its change over time to identify changes in direct and indirect soil use. However, there is the possibility that oil palm cultivation moves to livestock hectares, which eventually will diminish the rainforest hectares.

- *Technological dimension.*

The independent technological development — ITDC, driven by different investments, no longer had any effect on production costs for the year 2011. Moreover, technological development generated by learning as a consequence of biodiesel production in Colombia -

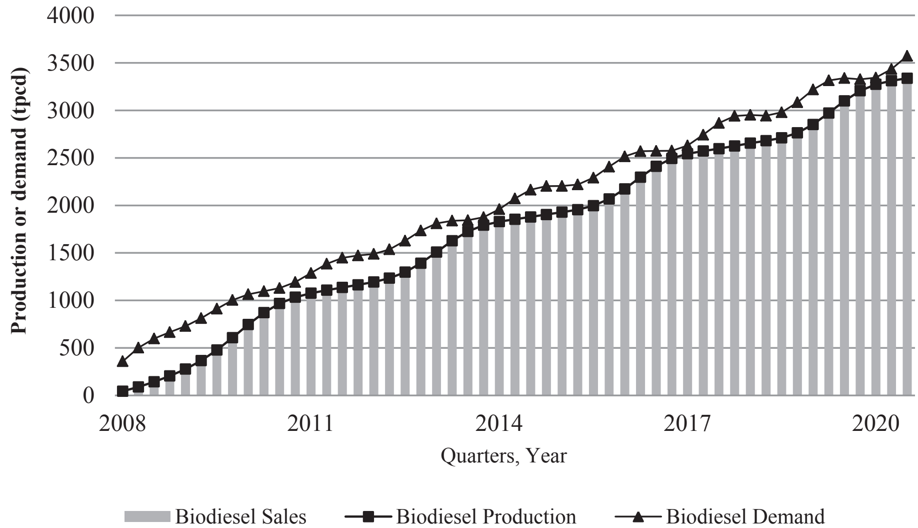

Fig. 9. Economic dimension, supply and demand.

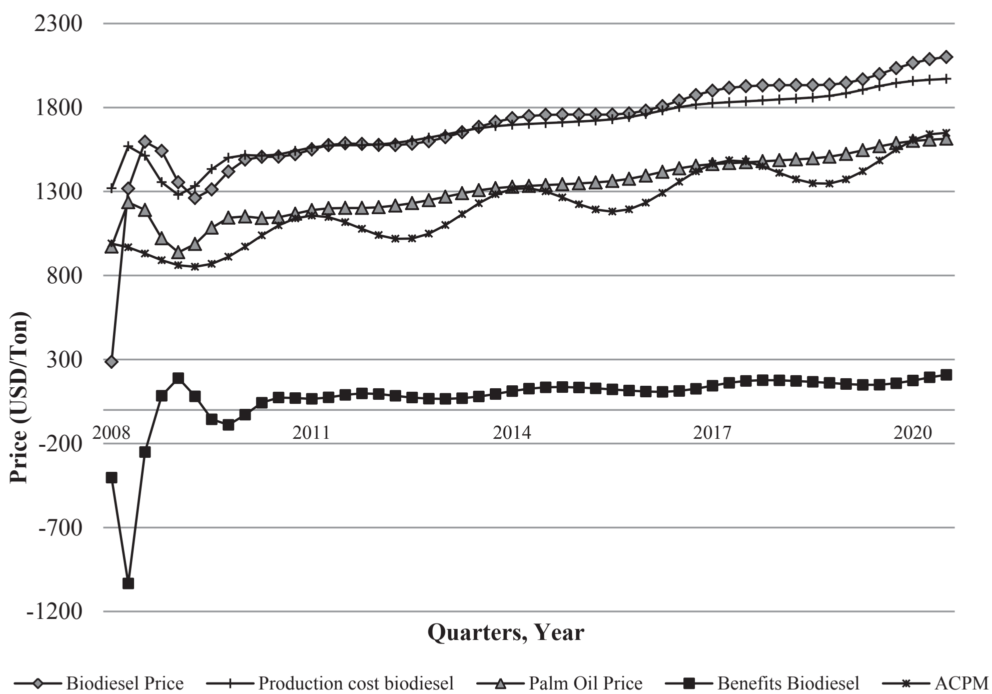

Fig. 10. Economic dimension, biodiesel price components and benefits.

LCDBP, will continue to generate a decrease in production costs until beyond 2020, but this decrease will be neglected (see Fig. 13). This implies a need to attract new investment and technology development to facilitate the competitiveness of biodiesel in the market in terms of production costs-PCBD, since the main component of his high production cost is the elevated raw material cost -RMC, which is palm oil price value.

5.2. Sensitivity analysis

The identification of most influential components of the biodiesel market in Colombia was done by applying a data visualization technique. Fig. 14 was constructed based on mathematical equations previously described. As a consequence, the figure shows the different variables of the dynamic system and its relations, emphasizing in a larger size and darkest color variables that had a greater number of relationships with others. The most influential components are *biodiesel production*, *palm oil price*, *palm hectares in production phase, palm oil production* and *palm hectares in development phase*. This graph enables us to easily observe that the biodiesel market is affecting the palm oil market, which will be analyzed more deeply in the sensitivity analysis.

The sensitivity analysis considers independent variables of the system, i.e. those external variables that influence their behavior

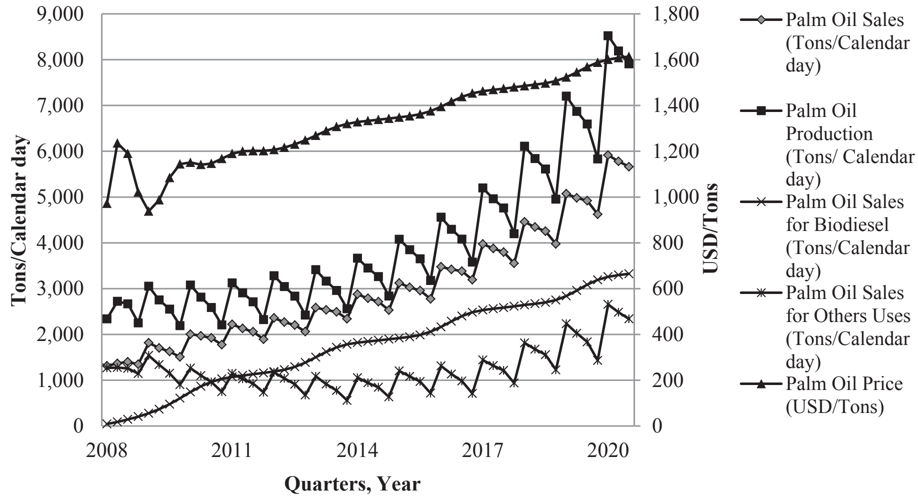

Fig. 11. Social dimension, impact on palm oil market.

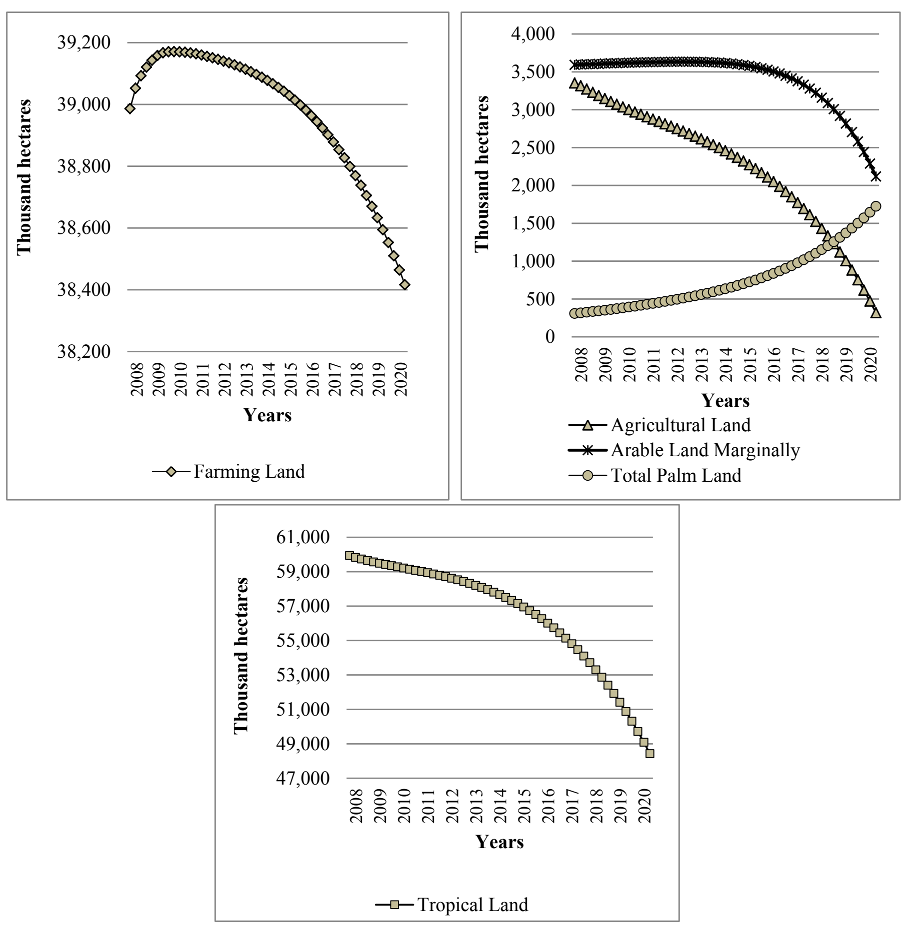

Fig. 12. Change in land use, impacts on agricultural, tropical, livestock and arable hectares marginally.

(Beltràn Vargas, 2012). Therefore, the analyzed variables are the value of the mixing ratio, the diesel price (ACPM), the oil price (WTI), diesel consumption, independent technology development, yield per hectare and seasonality. The analyses include five runs of the model for different values for each variable, for example, the percentage of mandatory blending was studied between zero and 50% and the yield of palm hectares to palm oil in a calendar day was varied between zero and 0.2 ton/Hectare Calendar Day.

– In the original model, the percentage of mandatory blending is between zero and 15.1%, so for the sensitivity analysis the range tested is between zero and 50%. Increasing the percentage of

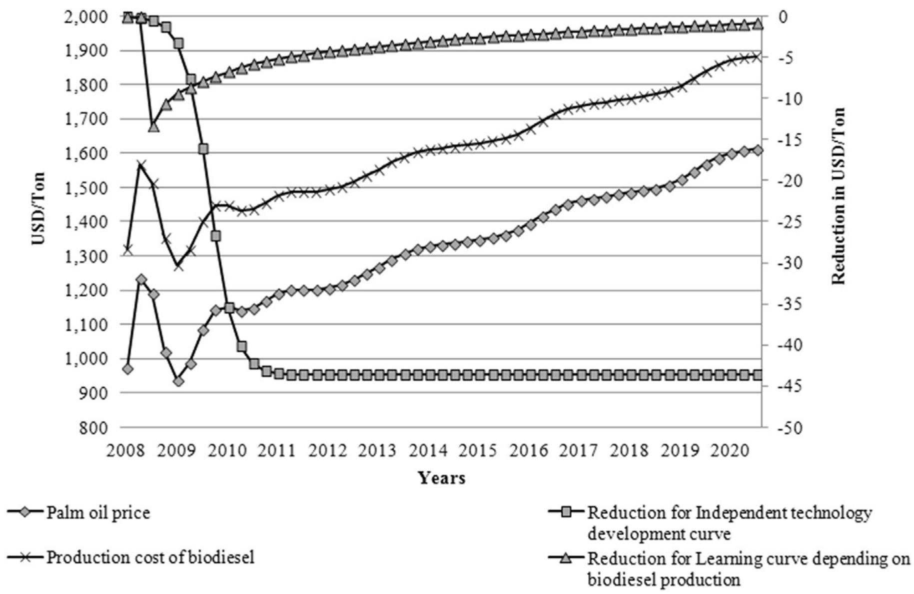

Fig. 13. Technological dimension.

mandatory blending in Colombia produces a rise in biodiesel sales, because there is an increase in biodiesel demand, as is show in Fig. 15. At the same time, it represents an incentive for augmenting biodiesel production. An increase in biodiesel and oil palm prices and better results in the benefits of selling biodiesel could be observed. For values such as 25% and more of the blending rate, the high palm oil price will disincentivize local consumption, incentivizing the purchase in other countries at the lowest price. The same result is obtained if diesel consumption increases. So, before proceeding with an increased percentage of requirement mixture of diesel with biodiesel, the importance of adjacent businesses, such as oleo-chemicals, must be discussed, as well as its possible protection through the deployment of government measures to prevent the

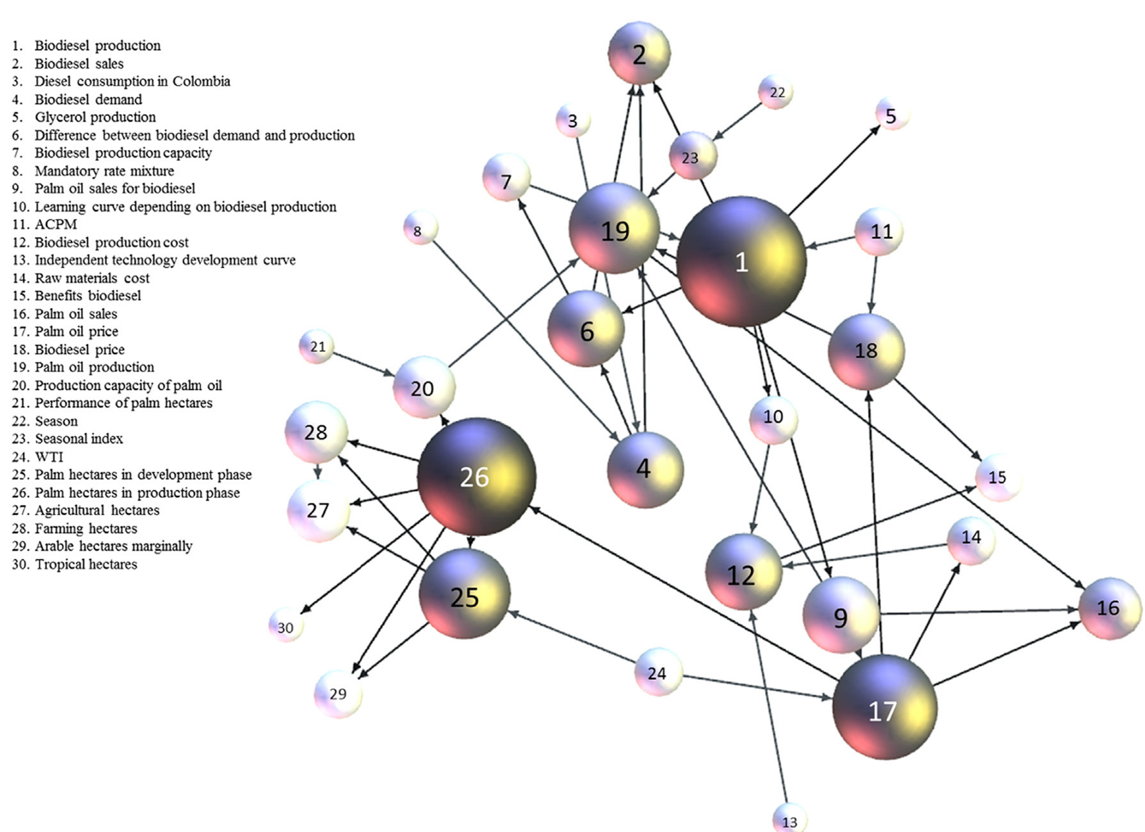

Fig. 14. Colombian government policies impact analysis.

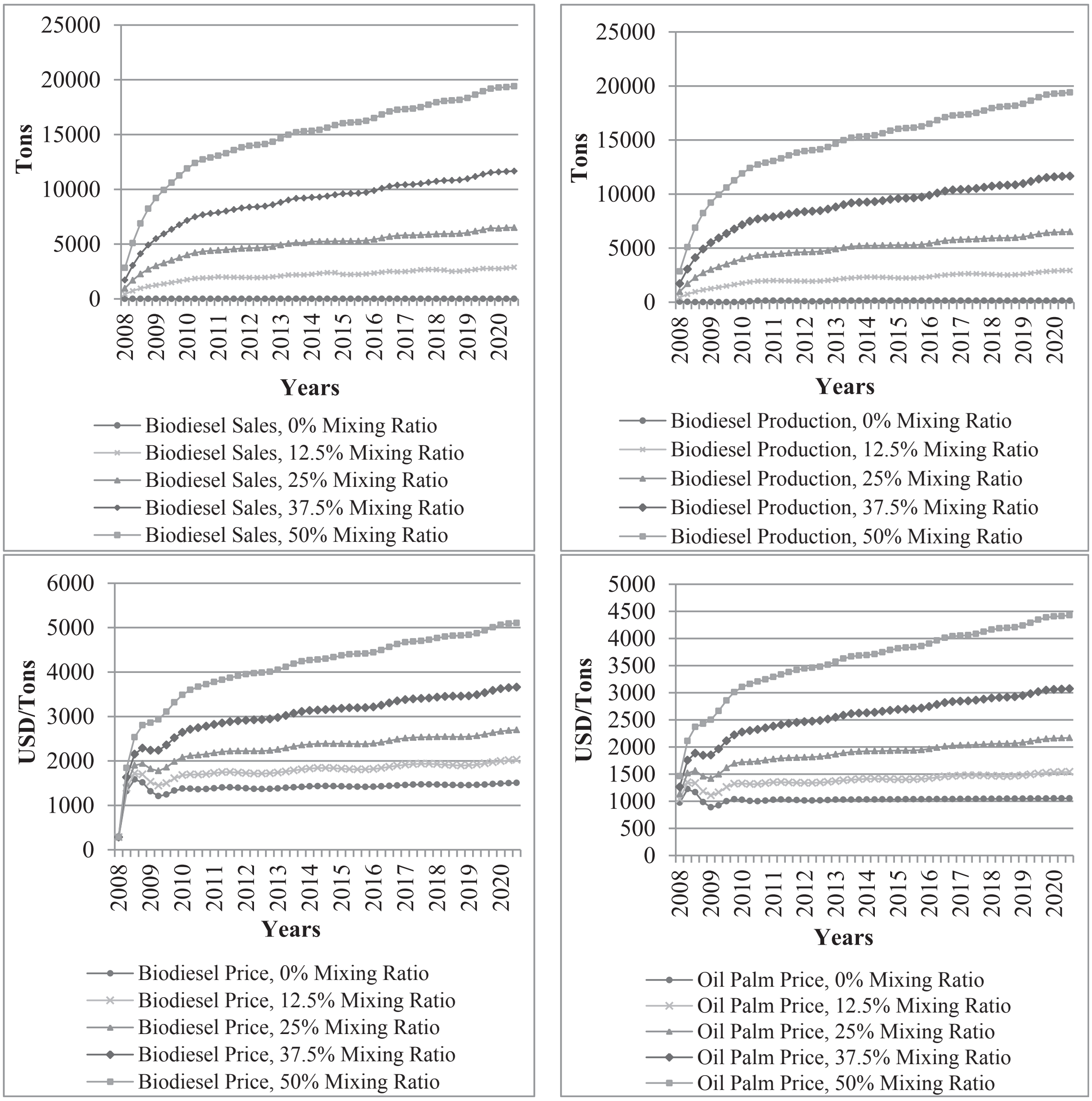

Fig. 15. Sensitivity analysis for percentage of mandatory blending in Colombia.

disappearance of these industrial activities and thereby decreasing jobs in Colombia. One of the options for such companies is to integrate the oleochemical industry with the biodiesel industry, transforming biodiesel production plants into biorefineries in order to get higher value added products, without neglecting the need to reduce production costs associated with the value of raw materials. On this last point, it should be noted that Colombia has a Price Stabilization Fund for Palmiste, Palm Oil and its fractions (Decreto 2025, 1996; Decreto 2354, 1996; Acuerdo 258, 2013) which allows producers of palm oil to profit by stabilizing mechanisms of transfer (fiscal contributions) and compensation (Payments to Fund resources) (Acuerdo 218, 2012), so there is no incentive to optimize production and reduce costs. These considerations allow us to conclude that the Colombian government's policies on mandatory biodiesel consumption in the country have a direct impact on incentives to produce biodiesel. However, this policy also has strong effects on the palm oil market, encouraging the planting of palms and investment to accelerate production, affecting industries that also depend on palm oil to develop their production.

– Diesel consumption has a similar influence to mandatory blending in the system, but in a lower magnitude. In the original model, diesel consumption was between 11,808 and 20,682 tons, but for the sensitivity analyses it was ranged between 5000 and 25,000 tons.
– The dynamic model uses WTI Prices between zero and 953 USD/Ton, thereby the sensitivity analysis was made with values between zero and 2000 USD/Tons. The model sensibility, presented on Fig. 16, shows that increases in the WTI oil price affects the palm oil market, because under this circumstance, the stakeholders expect increases in the blending rate by the government, so they invest in palm hectares in order to have production availability. If there is a decrease in WTI, there is an effect decreasing palm oil price, which directly discourages palm cultivation. This generates a decrease in palm oil production, according to the economic theory of supply. Furthermore, WIT price diminution leads to lower biodiesel prices. However, the biodiesel price reduction does not affect biodiesel sales,

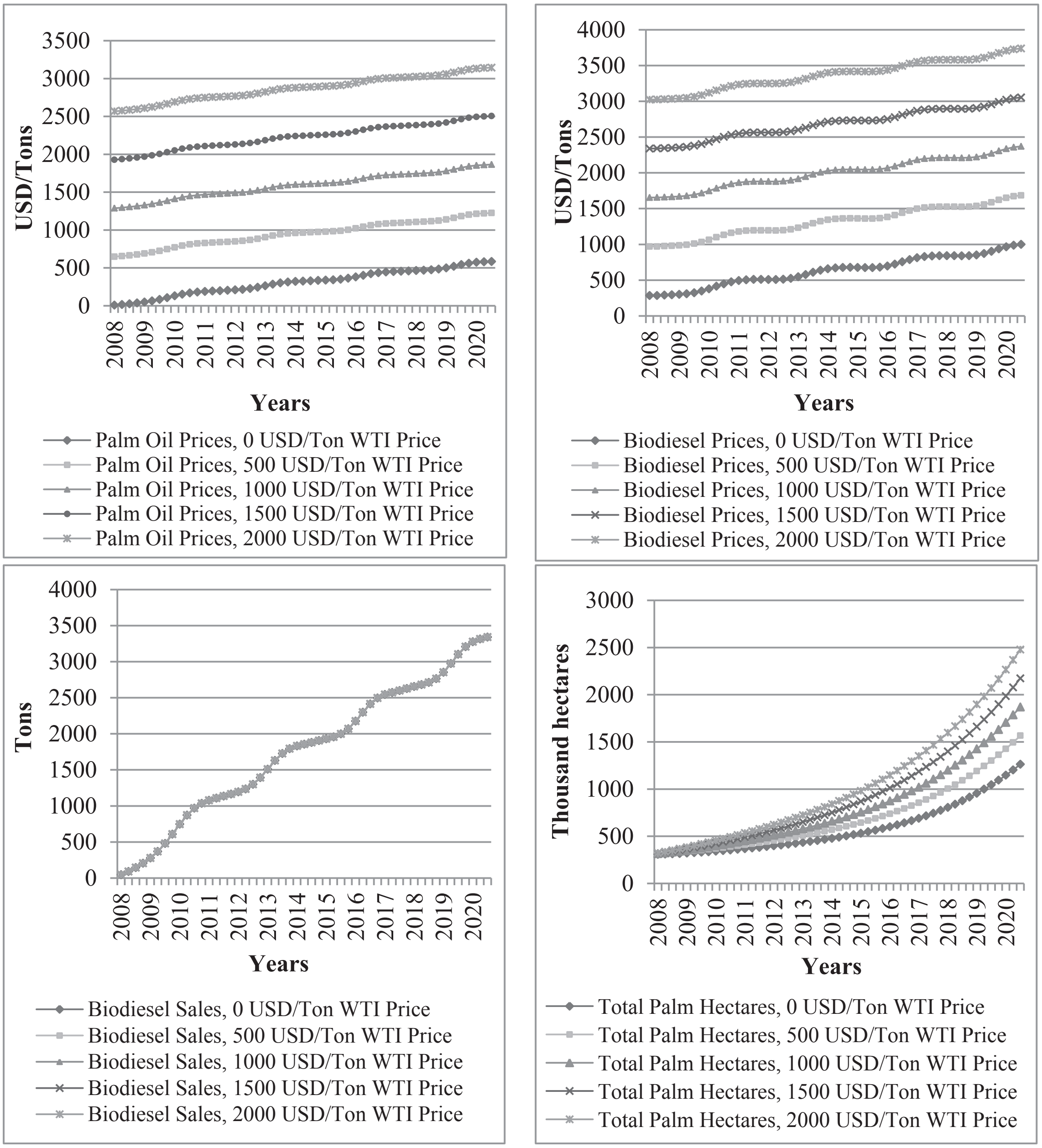

Fig. 16. Sensitivity analysis for WTI prices.

because the latter still depends on the required blending rate determined by the government.

- The ACPM price presented on the model fluctuates between 852 and 1649 USD/Ton and for the sensitivity analyses it takes values between 400 and 2400 USD/Ton. The increase in the price of diesel -ACPM leads to a higher biodiesel price, but does not significantly change biodiesel production, due to the inelasticity of biodiesel market, as is presented on Fig. 17.
- For analyzing the system sensitivity to independent technology development, its value was tested between zero and 100 USD/Ton de reduction on production cost, as is show on Fig. 18. It can be seen that the biodiesel price will no change at least the Colombian government consider the technologies improvements for the biodiesel price determination. The economic benefits for producers will increase, but it will not change market conditions due to the market inelasticity.
- The yield transformation from palm hectares on production to palm oil in the model was fixed to 0.01 Ton/Hectare Calendar day and for the sensitivity analyses it was tested between zero and 0.20 Ton/Hectare Calendar day. The augmentation on yield per hectare generates greater product availability, leading to a growth in palm oil sales, as is show on Fig. 19. These sales are mainly for other uses and not for biodiesel production. Therefore, a good policy could be to maximize yields of existing crops. A similar result is obtained if seasonality can be minimized and the maximum is produced every period.

6. Conclusions

This research presents a dynamic simulation modelling of the Colombian biodiesel market considering five sustainability dimensions. It allows the decision-makers to understand the

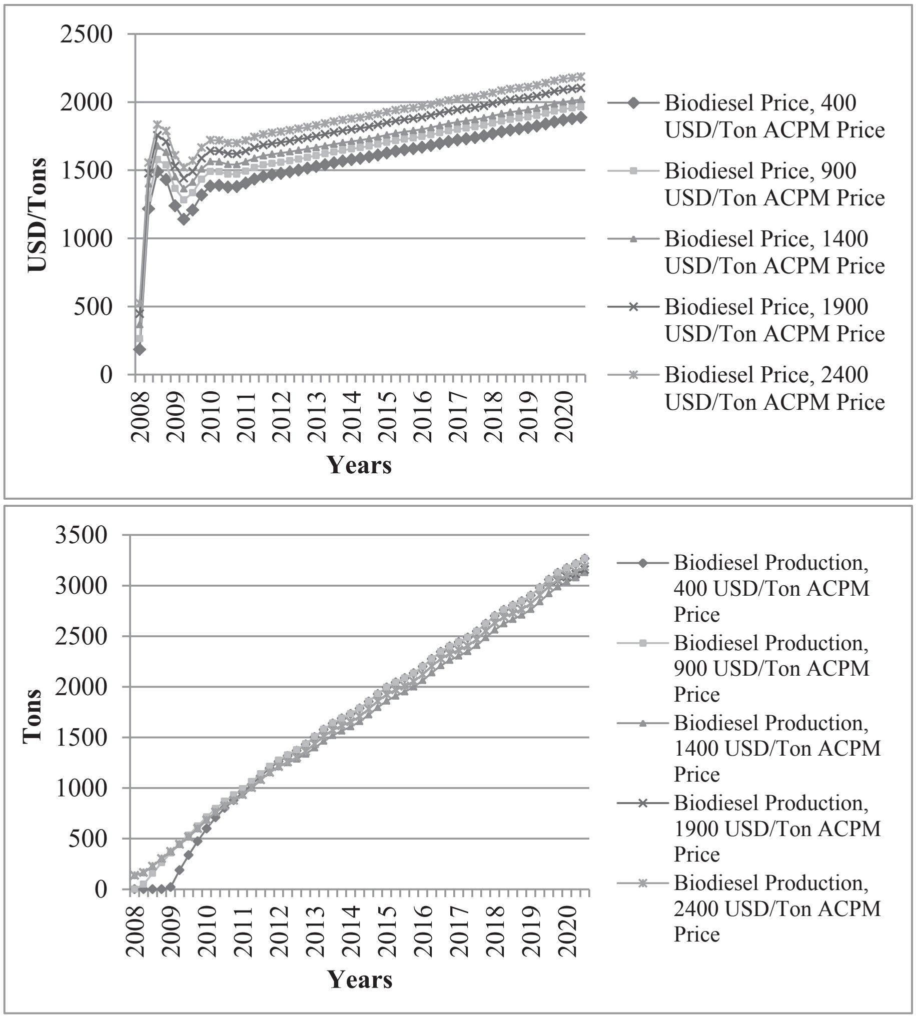

Fig. 17. Sensitivity analysis for ACPM prices.

influences between the different variables that describe the system and the impact of the government's biodiesel policy in Colombia. Furthermore, the system dynamics methodology description presented along with the different types of model validation permits the reproduction of the procedure performed.

Regarding the impacts of the Colombian government's policies, it will be concluded that these policies have generated a market similar to the market for diesel, characterized by consumption

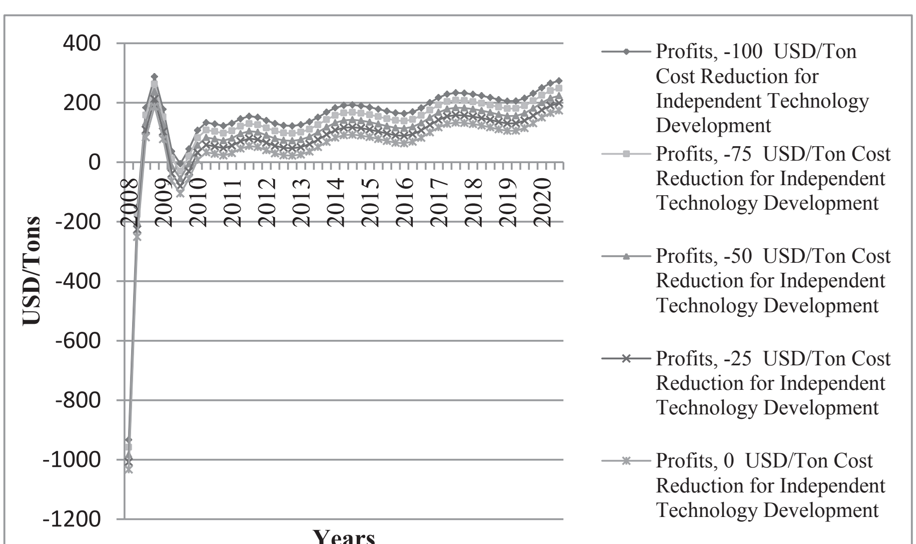

Fig. 18. Sensitivity analysis for independent technology development.

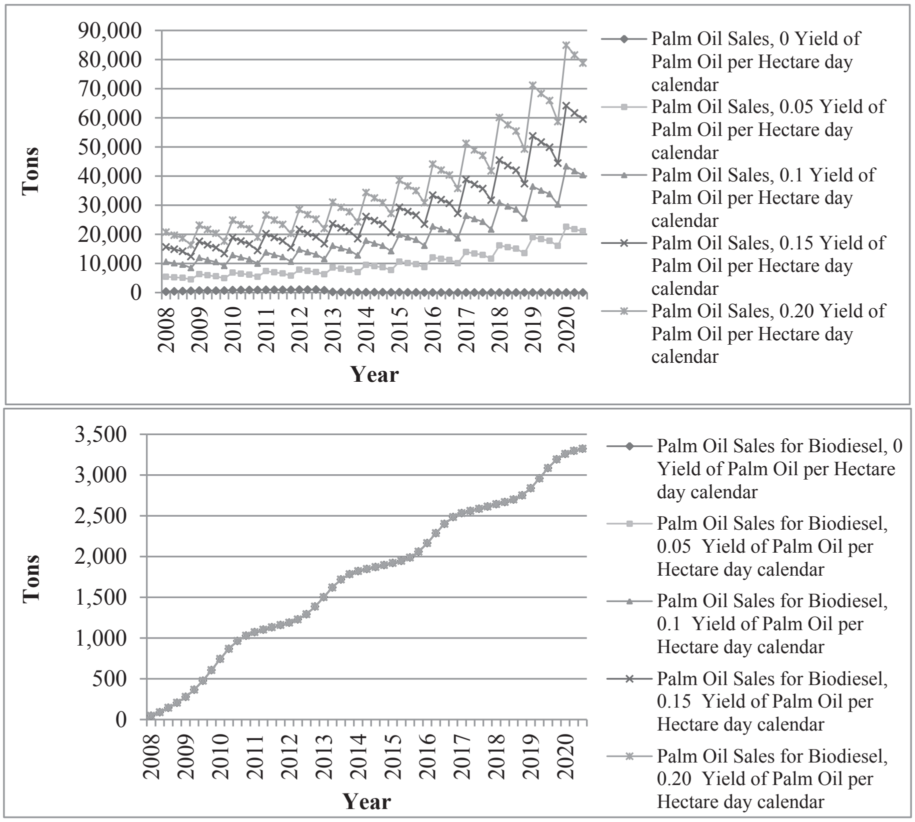

Fig. 19. Sensitivity analysis for yield of palm hectares to palm oil.

inelasticity in regard to the product price. Our simulations shown that, in spite of the biodiesel price, consumption will continue to grow.

From the sustainability point of view, while mandatory consumption creates demand, and thus generates the biodiesel industry, the impacts on land use and the palm oil market are also significant. Then, before proceeding to increase the required percentage of biodiesel to diesel – biodiesel blend, a study of the effects of higher production on agricultural and tropical lands must be accomplished. In any case, from the data gathered and the models fitted, it could be concluded that the biodiesel market and other internal factors have a big impact on agricultural and tropical lands.

The biodiesel price structured policy fixed by the government was defined, taking into account the generation of economic benefits for biodiesel producers. As a consequence, the biodiesel price is higher than the price of diesel, meaning that biodiesel will not be competitive under a non-regulated market. In order to reduce the high cost of biodiesel production, there are two options: first, to reduce the raw material cost through the achievement of higher palm cultivation yields and the improvement of agricultural practices and technologies and, second, to optimize the biodiesel production process. This could be achieved if the Colombian government made investments in specific research policy in the area of chemical process optimization for biodiesel production based on palm oil and investment in new production technologies for biodiesel based on other alternative raw materials.

Regarding land use, the Colombian government must encourage the intensified use of soil already planted with oil palm in order to decrease the negative impacts in other variables such as agricultural hectares. In parallel, it is necessary to supervise the use of agricultural land, which has been diminished in the last six years. This can be accomplished by an in-depth study for analysis of indirect land use, considering the geographic distribution of different types of land use over time for understanding the replacement, both direct and indirect, in land use type. This will permit the calculation of greenhouse gas emissions.

Between the different perspectives of this work, first, the dynamic model presented can be modified to analyze different policies before implementation, seeing its different impacts. Second, future work can be done with the methodology description, for analyzing other variables of interest to, for example, the government, social and environmental organizations, and industries. Including analyses such as the quantity of jobs created, the quantity of greenhouse gas emissions, and soil quality, among other variables.

Also, seen that the first value of biodiesel price has one of the biggest errors in the model, and it is caused because the first value of palm oil price given by the model has a big difference with the corresponding real value, it could be appropriated to consider data before the biodiesel production for determine the palm oil price, together with the evaluation of other variables not considered on the model that can influence the palm oil price.

Acknowledgements

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Appendix A. Characterization of variables

Variable	Notation	Unit of measurement	Source
Price of diesel ACPM	*ACPM*	USD/Ton	Sistema de Información de Petróleo y Gas Colombiano (SIPG)
Biodiesel production capacity	*BPC*	Tons calendar day	Federación Nacional de Combustibles de Colombia (FedeBiocombustibles)
Difference between biodiesel demand and production	*DBBDP*	Tons calendar day	Model
Accumulated biodiesel production	*ABP*	Tons calendar day accumulates per Quarter	Model
Production costs of biodiesel	*PCBD*	USD/Ton	Model
Raw materials cost	*RMC*	USD/Ton	Model
Palm oil price	*POPrice*	USD/Ton	Federación Nacional de Cultivadores de Palma de Aceite (Fedepalma) -Sistema de Información del Sector Palmero (SISPA)
Seasonally adjusted palm oil production	*SAPOP*	USD/Ton	Model
Production capacity of palm oil in the country	*PCPO*	Tons calendar day	Model
Palm oil sales for biodiesel	*POSFB*	Tons calendar day	FedeBiocombustibles
Biodiesel price	*BDPrice*	USD/Ton	FedeBiocombustibles
Time	T	Quarter	Model
Palm hectares in development phase	*PHID*	Hectares	Fedepalma -SISPA
International oil price WTI	*WTI*	USD/Ton	Servicio geológico Mexicano (SGM)
Agricultural hectares	*AH*	Hectares	Ministerio de agricultura y desarrollo rural, Colombia (MinAgricultura)
Biodiesel production	*BP*	Tons calendar day	FedeBiocombustibles
Change in biodiesel production capacity	*CBPC*	Tons calendar day/Quarter	Model
Learning curve depending on biodiesel production	*LCDBP*	USD/Ton	Model
Independent technology development curve	*ITDC*	USD/Ton	Model
Seasonal index	*SI*	Nondimensional	Model
Palm oil production	*POP*	Tons calendar day	Fedepalma -SISPA
Palm oil sales	*POS*	Tons calendar day	Fedepalma -SISPA
Variation of palm hectares in development phase to production status	*VPHIDTP*	Hectares/Quarter	Model
Stock level of biodiesel	*SB*	Ton	Model
Biodiesel sales	*BS*	Ton calendar day	FedeBiocombustibles
Glycerol production	*GP*	Ton calendar day	Model
Biodiesel demand	*BD*	Ton calendar day	Model
Mandatory rate mixture	*MRM*	%	Centro de investigación económica y social, Colombia (Fedesarrollo)
Diesel consumption in Colombia	*DCC*	Tons calendar day	Departamento Administrativo Nacional de Estadística, Colombia (DANE)
Accumulated difference between biodiesel demand and production	*ADBBDP*	Ton calendar day	Model
Glycerol price	*GPrice*	USD/Ton	DANE
Glycerol exportations	*GExp*	Thousands USD/Quarter	DANE
Variable auxiliary glycerol	*AuxG*	(Quarter × USD)/(Calendar day × thousand USD)	Model
Comparison glycerol production and exportation	*CGPE*	USD Calendar day	Model
Variable auxiliary of accumulated biodiesel production	*AuxABP*	Ton calendar day/Quarter	Model
Variable auxiliary of biodiesel price	*AuxBDPrice*	USD/Ton Quarter	Model
Benefits biodiesel	*BBD*	USD/Ton	Model
Stock of palm oil	*SPO*	Ton	Model
Performance of palm hectares	*PPH*	%	Fedepalma
Palm hectares in production phase	*PHIP*	Hectares	MinAgricultura
Palm hectares in development phase	*PHID*	Hectares	MinAgricultura
Abnormal development and death of palm in production	*ADDPP*	Hectares/quarter	MinAgricultura
Death of palm hectares in development	*DPHID*	Hectares/quarter	MinAgricultura
Total number of palm hectares	*TNPH*	Hectares	MinAgricultura (Encuesta Nacional Agropecuaria)
Variation of palm hectares in production phase	*VPHIP*	Hectares/quarter	MinAgricultura (Encuesta Nacional Agropecuaria)
Total variation of palm hectares seeds	*TVPHS*	Hectares/quarter	MinAgricultura (Encuesta Nacional Agropecuaria)
Arable hectares marginally	*AHM*	Hectares	MinAgricultura (Encuesta Nacional Agropecuaria)
Tropical hectares	*TH*	Hectares	MinAgricultura (Encuesta Nacional Agropecuaria)
Farming hectares	*FH*	Hectares	MinAgricultura (Encuesta Nacional Agropecuaria)
Variation on arable hectares marginally	*VAHM*	Hectares/quarter	Model
Variation on farming hectares	*VHF*	Hectares/quarter	Model
Variation on agricultural hectares	*VAH*	Hectares/quarter	Model
Variable auxiliary 1 of tropical hectares	*Aux*1*TH*	Hectares/quarter	Model
Variable auxiliary 2 of tropical hectares	*Aux*2*TH*	Hectares/quarter	Model
Variable auxiliary 1 of WTI	*Aux*1*WTI*	USD/(Ton Quarter)	Model
Variable auxiliary 2 of WTI	*Aux*2*WTI*	USD/(Ton Quarter)	Model

Appendix B. Principal equations

Eq.	Y	Equation
(1)	*BP*	$If(-946 + 0.75\ BPC + 0.897ACPM<0)Then\ 0\ Else\{IF(-946 + 0.75\ BPC + 0.897ACPM<BPC)Then-946 + 0.75\ BPC + 0.897ACPM\ Else\ BPC\}$
(2)	*CBPC*	$0{,}317DBBDP$
(3)	*LCDBP*	$If(1.59LN(ABP-142.6)-18.96<0)Then\{1.59LN(ABP-142.6)-18.96\}Else\ 0$
(4)	*ITDC*	$43{,}6 \Big/ (1 + 1885.01Exp(1)^{-Time})$
(5)	*SI*	$IF(Season = 1)Then\ 1.15\ Else\{IF(Season = 2)Then\ 1.06\ Else[IF(Season = 3)then\ 0.97\ Else\langle IF(Season = 4)Then\ 0.82\ Else\ 0\rangle]\}$
(6)	*POP*	$SAPOP\ SI$
(7)	*POS*	$765 + 0.650\ POSFB-0.588\ POPrice + 0.466\ POP$
(8)	*VPHIDTP*	$5450.76 + 0.001\ POPrice-486.12\ TIME + 18.61\ TIME^2 + 0.03\ PHID$

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