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Sandra Cecilia Bautista Rodríguez

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UNIVERSIDAD NACIONAL DE COLOMBIA

SUSTAINABILITY ASSESMENT OF BIODIESEL PRODUCTION IN COLOMBIA

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Universidad Nacional de Colombia

School of Engineering, Chemical and Environmental Engineering Department

Bogotá, D.C., Colombia

2015

SUSTAINABILITY ASSESMENT OF BIODIESEL
PRODUCTION IN COLOMBIA

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Presented as a partial requirement to qualify for the degree of:

PhD in Engineering – Chemical Engineering

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Bogotá, D.C., Colombia

2015



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Universidad Nacional de Colombia

School of Engineering, Chemical and Environmental Engineering Department

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2015

*I dedicate this thesis to the love of my life and light of my heart, my beloved husband
Vladimir.*

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RESUME

Évaluation de la durabilité de la production de biodiesel est un sujet d'importance croissante en raison de l'intérêt des gouvernements à effectuer des stratégies de souveraineté, diversifier leur matrice énergétique et mis en place l'impact de la production de biocarburants. Dans ce contexte, ce travail propose un modèle dynamique du système pour évaluer la production de biodiesel dans un contexte spécifique, basé sur une structure hiérarchique générale d'évaluation de la durabilité qui intègre les dimensions du développement durable avec les principes, critères et indicateurs (PC & I). Le cadre de l'évaluation de la production de biodiesel a été défini d'après une ample état de la technique, ce qui entraîne une sélection et analyse de 113 documents, y compris les lois, directives et autres documents normatifs, les documents de politique, les certificats et documents publiés dans des revues. Pour définir le cadre final, une stratégie de validation basée sur les consultations d'experts enquête et une analyse statistique descriptive a été réalisée. Ainsi, un cadre composé de cinq dimensions (sociales, économiques, environnementale, politiques et technologiques), 13 principes et 31 critères a été proposé.

Par la suite, un modèle de dynamique de système (DS) a été développé et appliqué pour évaluer la durabilité de la production du biodiesel en Colombie. Au départ, le modèle DS a été utilisé pour simuler la production du biodiesel, compte tenu des conditions actuelles en Colombie, ce qui permet de déterminer le niveau de référence (années 2008-2014). Par la suite, certains indicateurs exogènes du scénario de référence ont été modifiés afin de générer une analyse de sensibilité pour définir plusieurs conditions fondamentales vers la production de biodiesel durable dans le contexte colombien. Une fois l'analyse de sensibilité a été réalisée, on a déterminé les conditions qui favorisent ou découragent la production de biodiesel et, par conséquent, des scénarios optimistes et pessimistes ont été proposées. Les résultats de l'analyse des scénarios peuvent aider les institutions, les décideurs et les autres parte prenants associés à établir les conditions à réaliser pour promouvoir une production durable du biodiesel.

Mots clés: Évaluation de la durabilité, Production du biodiesel, dynamique des systèmes

ABSTRACT

Sustainability assessment of biodiesel production is a topic of increasing importance due to the interest of governments to establish sovereignty strategies, diversify their energy matrix and set up the impact of biofuels production. In this context, this work proposes a system dynamic model to assess biodiesel production in a specific context, based on a general hierarchical structure of sustainability assessment that integrates dimensions of sustainable development with principles, criteria and indicators (PC&I). The assessment framework of biodiesel production was defined based on a comprehensive state of the art, resulting in a selection and analysis of 113 documents, including laws, directives and other normative documents, policy documents, certificates and papers published in peer-reviewed journals. To define the final framework, a validation strategy based on expert survey consultations and a descriptive statistical analysis was conducted. As a result, a framework composed of five dimensions (social, economic, environmental, political and technological), 13 principles and 31 criteria was proposed.

Subsequently, a System Dynamics (SD) model was developed and applied for assess the sustainability biodiesel production in Colombia. Initially, the SD model was used to simulate the biodiesel production considering the current conditions in Colombia, enabling to determine the baseline (years 2008 to 2014). Subsequently, some exogenous indicators of the baseline scenario were modified in order to generate a sensibility analysis to define several fundamental conditions for the sustainable biodiesel production in the Colombian context. Once the sensibility analysis was conducted, the conditions that promote or discourage biodiesel production were determined and, consequently, optimistic and pessimistic scenarios were proposed. The results of the analysis of the scenarios can help institutions, decision-makers and other agents related to establish the conditions to be carried out to promote a sustainable biodiesel production.

Keywords: Sustainability assessment, biodiesel production, system dynamics

TABLE OF CONTENTS

Acknowledgments	5
RESUME.....	VI
ABSTRACT	VII
INTRODUCTION.....	VII
1. Chapter 1: Biodiesel-TBL+: A new hierarchical sustainability assessment framework of PC&I for biodiesel production	27
Introduction	27
1.1 Insight from previous literature	27
1.2 Methods	29
1.2.1 Search strategy of documents.....	29
1.2.2 Descriptive document analysis and selection.....	31
1.3 Results from the literature review	31
1.3.1 Descriptive analysis.....	31
1.3.2 Information Classification.....	34
1.3.3 Sustainability assessment dimensions.....	37
1.3.4 Frameworks previously used for sustainability assessment of biofuels.....	39
1.4 The Triple Bottom Line Extended (Biodiesel-TBL+), a new framework for biodiesel sustainability assessment	41
1.5 Application of the new assessment framework to biodiesel production	43
1.6 Discussions	46
Conclusions	49
2. Chapter 2: Principles and criteria validation for framework sustainability assessment of biodiesel production	51

Introduction	51
2.1 Hierarchical assessment framework	52
2.2 Validation method of sustainability assessment principles and criteria for biodiesel production.....	53
2.2.1 Expert identification.....	53
2.2.2 Survey design	55
2.2.3 Survey application.....	56
2.2.4 Descriptive statistics analysis.....	56
2.2.5 Selection of sustainability assessment principles and criteria for biodiesel production.....	58
2.2.6 Data visualization of principles and criteria selected.....	59
2.3 Results	59
2.3.1 Expert profile description.....	59
2.3.2 Principles statistics analysis	60
2.3.3 Criteria statistical analysis.....	63
2.4 Selection of sustainability assessment principles and criteria	71
2.5 Analysis of the principles and criteria recommended	73
2.6 Data visualization technique of principles and criteria	74
Conclusions	76
3. Chapter 3: Definition and design of a system dynamic model for sustainability assessment of biodiesel production in Colombian context	79
Introduction	79
3.1 Background of Colombian biodiesel production.....	79
3.2 System dynamics application in biofuels analysis	80

3.3	Systems dynamics methodology	82
3.3.1.	Problem formulation	82
3.3.2.	Dynamic hypothesis formulation	83
3.3.3.	Description of the model boundary	84
3.3.4.	Description of the model structure and the equation definition	84
3.3.5.	Testing and analysis	85
3.4	Application of SD methodology in the biodiesel sustainability assessment	86
3.4.1	Problem formulation	86
3.4.2	Dynamic hypothesis formulation in the biodiesel sustainability assessment – Causal loop cycles	87
3.4.3	Description of the model boundary	97
3.4.4	Description of the model structure and equations	101
	• Biodiesel production sub-model	102
	• Land and social sub-model	105
	• Net energy ratio sub-model	109
	• Water demanded sub-model	112
	• Greenhouse gas emissions saving in life cycle of biodiesel sub-model	113
	• Pollutant emission that affect air quality as a consequence of the use of biodiesel - diesel blends as biofuel sub-model.....	116
3.4.5	Testing and analysis	117
	Conclusions	119
4	Chapter 4: System dynamic model of sustainability assessment of biodiesel production in Colombian context - Results	121

Introduction	121
4.1 Baseline	121
4.1.1 Economic dimension	122
4.1.2 Social dimension	124
4.1.3 Environmental dimension	125
4.1.4 Political dimension	130
4.1.5 Technological dimension	131
4.2 Sensitivity analysis	133
4.2.1 Oil price	133
4.2.2 Diesel powered vehicles	135
4.2.3 Factor of direct contracted employees in oil palm cultivation – FDCEPC	136
4.2.4 Costs linked to biodiesel policy	137
4.2.5 Factor of agrochemicals applied in land for palm cultivation – FAALPC	139
4.2.6 Biodiesel-diesel blend (Mix ratio)	140
4.2.7 Technological efficiency factor of first generation biodiesel (palm-oil consumed per biodiesel produced)	141
4.2.8 Factor of land use change of rain forest to oil palm cultivation - FLUCFP	143
4.2.9 Sensitivity analysis summarized	144
4.3 Scenario analysis	144
4.3.1 Optimistic scenario	145
4.3.2 Pessimistic scenario	153
4.4 Scenario analysis discussion	161
4.4.1 Economic dimension	162

4.4.2 Social dimension	162
4.4.3 Environmental dimension	162
4.4.4 Political dimension.....	162
4.4.5 Technological dimension	163
Conclusions	163
5 Chapter 5: Conclusions and recommendations	165
5.1 Conclusions	165
5.2 Limitations.....	166
5.3 Recommendations	167
6 References	171
Appendix	183
Appendix 1. Document linked to principles, criteria and indicator.	183
Appendix 2. Constant of equations model	191
Appendix 3. Model indicator: statistics issues	195
Appendix 4. Online survey.....	215
Appendix 5 Technological description of Propanediol production (PDO).....	221

LIST OF TABLES

Table 1-1. Previous literature	28
Table 1-2 Classification of selected documents	34
Table 1-3. Definitions of principles, criteria and indicators	41
Table 2-1. Importance grading scale of principles and criteria.....	55
Table 2-2. Grading averages of principles' importance	61
Table 2-3. Average grading criteria for attribute	63
Table 2-4. Correlation matrix between criteria attributes	65
Table 2-5. Characteristics of criteria groups	68
Table 2-6. Sustainability assessment criteria recommended.....	72
Table 3-1 Endogenous indicators	97
Table 3-2 Exogenous indicators	98
Table 3-3 Stock and flow equations by biodiesel production sub-model	102
Table 3-4 Output indicator from biodiesel production sub-model.....	105
Table 3-5 Stock and flow equations by land and social sub-model	106
Table 3-6 Input indicator used in land and social sub-model	109
Table 3-7 Output indicator from land and social sub-model.....	109
Table 3-8 Stock and flow equations by net energy ratio sub-model	111
Table 3-9 Inputs indicators used in net energy ratio sub-model	111
Table 3-10 Stock and flow equations by water demand sub-model.....	112
Table 3-11 Inputs indicators used in water sub-model.....	113
Table 3-12 Stock and flow equations by GHG emissions saving in life cycle of biodiesel sub-model.....	113
Table 3-13 Inputs indicators used in GHG emission saving in life cycle of biodiesel sub-model	116
Table 3-14 Stock and flow equations by pollutant emission sub-model.....	116
Table 3-15 Inputs indicators used in pollutant emission that affect air quality: biodiesel blended by diesel sub-model.....	117

Table 3-16 Dynamic model validation using MAPE	118
Table 4-1 Input and output indicators in sensitive analyse	133
Table 4-2 Summary of sensitivity analysis (sensitivity kind: no sensitive, low increment, high increment, low diminish, high diminish).....	144
Table 4-3 Optimistic scenario conditions.....	145
Table 4-4 Pessimistic scenario conditions	154

LIST OF FIGURES

Figure 1-1. Document temporal distribution.....	32
Figure 1-2. Distribution of document in the information sources.....	33
Figure 1-3. Documents by subject area.....	33
Figure 1-4. Geographical distribution of documents.....	34
Figure 1-5. Percentages of document by classification group of documents.....	36
Figure 1-6. Number of papers cited specifically by criterion.....	37
Figure 1-7. General frameworks employed to perform the sustainability assessment of biodiesel.....	40
Figure 1-8. Biodiesel sustainability framework (Bautista et al. 2016).....	43
Figure 1-9. Social dimension: principles and criteria.....	44
Figure 1-10. Political dimension: principles and criteria.....	44
Figure 1-11. Economic dimension: principles and criteria.....	45
Figure 1-12. Technological dimension: principles and criteria.....	45
Figure 1-13. Environmental dimension: principles and criteria.....	46
Figure 1-14. Number of principles and criteria by sustainable development dimensions TBL+.....	47
Figure 2-1. Validation Method of Sustainability Assessment Principles and Criteria for Biodiesel Production.....	54
Figure 2-2. Algorithm of descriptive statistics analysis.....	57
Figure 2-3. Number of experts by geographic region.....	59
Figure 2-4. Percentage of experts by type of organization.....	60
Figure 2-5. Proportion of the experts by expertise area.....	60
Figure 2-6. Principles importance, average and variation coefficient (Cv).....	62
Figure 2-7. PCA loading plots concerning the type of organization.....	62
Figure 2-8. Criteria importance, average and variation coefficient (Cv).	64
Figure 2-9. C:Scatter plot and box plot of correlation between criteria attributes (reliability and ease of measurement).....	66
Figure 2-10. PCA loading plot concerning the geographical sector of the experts.....	66

Figure 2-11. PCA loading plot concerning the experts' fields of expertise.....	67
Figure 2-12. PCA loading plot concerning the type of organization	68
Figure 2-13. Dendrogram of the HAC concerning the criteria.....	68
Figure 2-14. Point cloud of the social dimension.....	69
Figure 2-15. Point cloud of the political dimension.....	70
Figure 2-16. Point cloud of the economical dimension	70
Figure 2-17. Point cloud of the technological dimension	71
Figure 2-18. Point cloud of the environmental dimension.....	71
Figure 2-19. Principles and criteria framework visualization	76
Figure 3-1 System Dynamics methodology, based on (Lee et al. 2012b) and (Bérard 2010) .	82
Figure 3-2 Causal loop diagrams of the economic dimension	88
Figure 3-3 Causal loop diagrams of the social dimension	90
Figure 3-4 Social, environmental and economic indicators. Based on DANE (2013), Fedebiocombustibles (2015) and MA (2013).	91
Figure 3-5 Causal loop diagrams of the environmental dimension	92
Figure 3-6. Causal loop diagrams of the technological dimension	94
Figure 3-7 Causal loop diagrams of the political dimension	95
Figure 3-8 Causal loop diagram integrated	96
Figure 3-9. Biodiesel production sub-model.....	104
Figure 3-10 Graphical function of cost linked to biodiesel politic in current situation	105
Figure 3-11 Others Biodiesel Production Costs Independent of Biodiesel Production	105
Figure 3-12 Graphical function of international production of biodiesel of second and third generation	105
Figure 3-13 Land and social sub-model	108
Figure 3-14 Graphical function of oil price based on EIA (2015)	108
Figure 3-15 Net energy ratio sub-model	110
Figure 3-16 Water sub-model	113
Figure 3-17 GHG emissions saving in life cycle of biodiesel sub-model.....	115

Figure 3-18 Pollutant emission that affect air quality: Biodiesel blended by diesel sub-model	117
Figure 4-1 Graphical output of economic indicators of model in baseline	123
Figure 4-2 Graphical output of economic indicators of model in baseline	123
Figure 4-3 Graphical output of economic indicators of model in baseline	123
Figure 4-4 Graphical output of social indicators of model in baseline	124
Figure 4-5 Graphical output of social indicators of model in baseline	125
Figure 4-6 Graphical output of environmental indicators of model in baseline	126
Figure 4-7 Graphical output of environmental indicators of model in baseline scenario	126
Figure 4-8 Graphical output of environmental indicators of model in baseline scenario	127
Figure 4-9 Graphical output of environmental indicators of model in baseline scenario	127
Figure 4-10 Graphical output of environmental indicators in baseline scenario	128
Figure 4-11 Graphical output of environmental indicators of model in baseline scenario	128
Figure 4-12 Graphical output of environmental indicators of model in baseline scenario	129
Figure 4-13 Graphical output of environmental indicators of model in baseline	129
Figure 4-14 Graphical output of environmental indicators of model in baseline	130
Figure 4-15 Graphical output of environmental indicators of model in baseline	130
Figure 4-16 Graphical output of politics indicators of model in baseline.....	131
Figure 4-17 Graphical output of technological indicators of model in baseline	132
Figure 4-18 Graphical output of technological indicators of model in baseline scenario.....	132
Figure 4-19 Sensitivity analyse of Oil price on the output indicators.....	134
Figure 4-20 Sensitivity analyse of diesel vehicles on the output indicators	136
Figure 4-21 Sensitivity analyse of FDCEPC on the output indicators.....	137
Figure 4-22 Sensitivity analyse of cost linked to biodiesel politics on the output indicators	138
Figure 4-23 Sensitivity analyse of factor agrochemical applied in oil palm cultivation on the output indicators	140
Figure 4-24 Sensitivity analyse of mix ratio biodiesel -diesel on the output indicators	141
Figure 4-25 Sensitivity analyse of efficiency factor technological on the output indicators .	143

Figure 4-26 Sensitivity analyse of factor of land use change of forest lands to oil palm cultivation on the output indicators	144
Figure 4-27 Graphical output of economic indicators of model in optimistic scenario.....	146
Figure 4-28 Graphical output of economic indicators of model in optimistic scenario.....	147
Figure 4-29 Graphical output of economic indicators of model in optimistic scenario.....	147
Figure 4-30 Graphical output of social indicators of model in optimistic scenario	148
Figure 4-31 Graphical output of social indicators of model in optimistic scenario	148
Figure 4-32 Graphical output of environmental indicators of model in optimistic scenario .	149
Figure 4-33 Graphical output of environmental indicators of model in optimistic scenario .	149
Figure 4-34 Graphical output of environmental indicators of model in optimistic scenario .	149
Figure 4-35 Graphical output of environmental indicators of model in optimistic scenario .	150
Figure 4-36 Graphical output of environmental indicators of model in optimistic scenario .	150
Figure 4-37 Graphical output of environmental indicators of model in optimistic scenario .	151
Figure 4-38 Graphical output of environmental indicators of model in optimistic scenario .	151
Figure 4-39 Graphical output of environmental indicators of model in optimistic scenario .	151
Figure 4-40 Graphical output of environmental indicators of model in baseline scenario	152
Figure 4-41 Graphical output of politic indicators of model in optimistic scenario	152
Figure 4-42 Graphical output of technological indicators of model in optimistic scenario...	153
Figure 4-43 Graphical output of technological indicators of model in optimistic scenario...	153
Figure 4-44 Graphical output of economic indicators of model in pessimistic scenario	155
Figure 4-45 Graphical output of economic indicators of model in pessimistic scenario	156
Figure 4-46 Graphical output of economic indicators of model in pessimistic scenario	156
Figure 4-47 Graphical output of social indicators of model in pessimistic scenario	157
Figure 4-48 Graphical output of social indicators of model in pessimistic scenario	157
Figure 4-49 Graphical output of environmental indicators of model in pessimistic scenario	157
Figure 4-50 Graphical output of environmental indicators of model in pessimistic scenario	158
Figure 4-51 Graphical output of environmental indicators of model in pessimistic scenario	158

Figure 4-52 Graphical output of environmental indicators of model in pessimistic scenario	159
Figure 4-53 Graphical output of environmental indicators of model in pessimistic scenario	159
Figure 4-54 Graphical output of environmental indicators of model in pessimistic scenario	159
Figure 4-55 Graphical output of environmental indicators of model in pessimistic scenario	160
Figure 4-56 Graphical output of politic indicators of model in pessimistic scenario	160
Figure 4-57 Graphical output of technological indicators of model in pessimistic scenario .	161
Figure 4-58 Graphical output of technological indicators of model in pessimistic scenario .	161

INTRODUCTION

Global implications associated with the use of fossil fuels, such as variation in fuel prices, the future limitation of their offer and governments' concerns about energy security and sovereignty, encourage the development of alternative renewable energy sources. This is the case of biomass used as feedstock to produce bioenergy, biofuels and bio-based products. Similarly, the growing demand for energy and the efforts of industrialized countries to reduce their carbon emissions, especially in the transport sector, promote the production of renewable biofuels (Edgard Gnansounou 2011).

Nowadays, one of the most commonly used biofuels is biodiesel. Initially, it was defined as a mixture of mono-alkyl esters of fatty acids obtained from vegetable oils and fats (ASTM D6751 2011). However, regarding the new developments and needs of the biofuels sector, its definition has evolved to include other types of biodiesel such as advanced biodiesel and biomass-based diesel (Epa 2010). These new definitions include the former biodiesel (mono-alkyl esters), as well as non-ester renewable diesel (covering cellulosic diesel), which composition is similar to petroleum-derived diesel, and it could be obtained from biomass, including vegetable oils, fats and cellulosic biomass (Epa 2010). Despite the previous fact, most common biodiesel produced industrially is a mixture of mono-alkyl esters of fatty acids (FAME), obtained by methanolysis of oils extracted from rapeseed, soybean and oil palm fruit.

Most industrial biodiesel production is performed by a conventional process, using a homogeneous alkaline catalyst, usually sodium or potassium methoxides. Separation steps use water as extracting agent for salts produced by catalyst neutralization, soaps, remaining free glycerol and other undesirable compounds present in the biodiesel rich stream obtained after the transesterification, settling and neutralization stages. Renewable non-ester biodiesel can be produced from vegetable oils by pyrolysis or hydrotreating, although industrial production is not fully developed yet. Despite the latter fact there is no doubt that renewable non-ester biodiesel will play a leading role in the future of biofuels (Pavlivna 2012).

The main arguments for promoting biofuels are their potential positive effects on environmental, economic and social dimensions because they would help humankind to reduce the negative impacts of burning fossil fuels and to extend non-renewable resource availability while a sustainable feedstock for energy and chemical products is found (Hill et al. 2006). In addition, employment generation, especially in rural areas of developing countries, would allow the governments to implement policies to reduce poverty and inequality. Unfortunately, negative effects of biofuel production on the dimensions previously mentioned gradually changed the perception of this bioenergy and opened a debate about its sustainability. Some of the negative effects include alteration of ecosystems, degradation and loss of soil and water, changes in tenure and land use, impact on food security, the negative balance of greenhouse gases in the life cycle of biofuels, and the economic viability of their production (Hill et al. 2006; Gnansounou 2011; Janssen and Rutz 2011).

Likewise, in the debate on the sustainability of biodiesel production, studies show conflicting results on the same topic. For example, while Directive 28/2009 of the European Union (C. E. EC and EP 2009) reports savings in greenhouse gas (GHG) of biodiesel obtained from rapeseed, soybean and palm oils up to 45%, 40% and 36%, respectively, in comparison to the fossil fuel replaced, other studies claimed that global GHG emissions increases due to changes in land use. This is because farmers react to the increase in the price of vegetable oils converting forests, peat-lands, savannahs or grasslands into further farmland to obtain the raw materials for biofuels. At the same time, other farmers plant traditional crops which were replaced by raw materials for biofuel crops (Fargione et al. 2008; Searchinger et al. 2008).

Another example of conflicting results about the impact of biodiesel production is the results presented by Hill et al. (2006) and Frondel & Peters (2007). Hill et al (2006), who analyzed the life cycle of biodiesel from soybean oil, reported that it produces about 93% more energy than needed to be obtained, as well as reducing greenhouse gas by 41% compared to diesel it replaces; it reduces several pollutants and has minimal impact on human health and the environment through the release of N, P and pesticides. Frondel and Peters (2007) stated that the use of biodiesel, instead of conventional diesel, contributes less than 100% of the fossil energy contained in conventional diesel. Additionally, they reported the negative effects on the environment during the biomass production stage (consumption of natural resources, increased soil acidification and pollution of surface waters due to the dumping of pesticides) and burning (increased NO_x emissions).

Otherwise, despite the social benefits associated with employment generation and improvements in education, health, income and housing of the population closer to the lands where biomass is grown, negative effects on food security and food prices, land use and tenure, violence, forced displacement and low job quality should also be considered (Phalan 2009). It was also observed that, in situations where biodiesel production is no longer economically viable, or with lower short-term returns (Hoon and Gan 2010), governments must set up policies related to tax exemptions and pricing schemes (Craven 2011). An artificial market which is too reliant on support measures such as government policies, subsidies and tax exemptions would collapse once these policies and incentives are withdrawn (Hoon and Gan 2010).

Regarding the previously mentioned context, emerging studies have implemented different methodologies to establish probable future scenarios where sustainable production of biodiesel could be achieved. Relevant examples include studies in South Africa (Josephine K. Musango et al. 2011; Josephine K. Musango et al. 2012; Brent and Musango 2013), Brazil (Milazzo et al. 2013), Chile (Iriarte, Rieradevall, and Gabarrell 2012), Latin America (Cepal 2011; Janssen and Rutz 2011), China (Wang, Calderon, and Lu 2011), India (Schaldach, Priess, and Alcamo 2011), Europe (Ulgiati, Russi, and Raugei 2008; Malça and Freire 2011) and Malaysia (Lim and Teong 2010), among others. Although results obtained answered some of the questions related to sustainable biofuel production, they generated additional enquiries that should be resolved. For example, there is no consensus on the dimensions to be considered to define in a comprehensive manner the conditions defining sustainable production, nor on specific metrics that would make it possible to measure the level of sustainability.

In the search for methods and tools to solve such issues, organizations and researchers have proposed strategies such as certification schemes or voluntary standards to ensure sustainability in an international market for bioenergy (Delzeit and Holm-Müller 2009), regulatory frameworks associated with directives, standards and laws applicable to a particular country, and frameworks or schemes related to control standards and indicators (Scarlat and Dallemand 2011). Examples of these include system certifications such as the Roundtable on Sustainable Palm Oil, the Roundtable and Responsible Soy, carbon certificates, CEN (European Committee for Standardization), standards for sustainable biomass production in bioenergy applications, and the Roundtable for Sustainable Biofuels, among many others (FAO and BEFSCI 2011). The most recognized regulatory frameworks are the renewable energy directive of the European Parliament, the Renewable Fuel Standard in the United States, and the mandate of renewable biomass in Germany. Among the control and command schemes for sustainable biofuels, those

established by the Inter-American Development Bank and the control scheme of the World Bank and World Wide Fund for Nature (WWF) deserve to be mentioned (Scarlat and Dallemand 2011).

The certification and assessment strategies mentioned above have in common that they consider the impact of biofuel production on sustainable development dimensions (traditionally the social, environmental and economic dimensions), but with these strategies it is difficult to show whether there are interdependencies or to measure the influence between impacts. Additionally, the influence of technological changes (e.g. changes in raw materials or production routes), political changes (international agreements, local regulatory standards), life quality of communities, or economic variations such as changes in oil prices, food prices or cropland price issues are weakly considered by the strategies of certification and evaluation.

Despite the efforts previously mentioned, there are still problems to overcome, as the lack of metrics to evaluate some dimensions of biodiesel sustainability and, especially, the absence of tools to determine effectively the relationships between them. There are five main reasons for these problems: The first is biodiesel supply chain is a multistage process, involving from the production of raw materials (mainly biomass), oil extraction, and biodiesel transformation, to the storage, transportation blending and sell of the final product. The second reason is the complex relationships between the geographical and cultural contexts of the biodiesel supply chain. The third refers to the various actors and stakeholders involved (Awudu and Zhang 2012). The fourth is associated with achieving a set of dimensions sufficiently holistic and comprehensive of sustainable development that embraces the relationships between social, economic, political, technological and environmental variables, and finally, the fifth reason is the difficulty of establishing an evaluation framework to assess these dimensions.

Considering the need for a sustainability assessment that addresses the problems mentioned above, the general objective of this research is to define a framework that allows the actors and stakeholders of biodiesel supply chain to assess the sustainability of biodiesel production through the integration of the sustainability theory and the system dynamic modeling as a methodological approach.

In this work a hierarchical framework of 13 principles, 31 criteria and 150 indicators was proposed and validated for the sustainability assessment of biodiesel production. It integrates the three traditional dimensions of sustainable development and two new dimensions: political

and technological. After that, a system dynamics based model was designed and implemented using Stella® software. It permits the visualization of the relationships inside a dimension and between dimensions through causal loop diagrams (CLD), which despite of its simplicity, play a central role in the conceptualization and communication of feedback structure (Lee et al. 2012a).

Finally, the CLD were integrated and converted into a quantitative model, called the stock and flow diagram, used to simulate biodiesel production in the Colombian context under three scenarios: baseline, optimistic and pessimistic. A sensitivity analysis was performed with the aim to identify some conditions that will promote or discourage a sustainable biodiesel production in 2030.

This thesis presents in five chapters the problem involved to assess the sustainability of biodiesel production in the Colombian context, and the 2030 scenario. Chapter 1 shows the method to establish the sustainability assessment framework of biodiesel production, based on a comprehensive state of the art, resulting in the selection and analysis of 113 documents, including laws, directives and other normative documents, policy documents, certificates and papers published in peer-reviewed journals. Chapter 2 describes the method to define the final framework through a validation strategy based on expert survey consultations and a descriptive statistical analysis. In order to elucidate the principles and criteria importance for sustainability assessment of biodiesel, 62 experts answered an online survey. As a result, a framework composed of five dimensions (social, economic, environmental, political and technological), 13 principles and 31 criteria that would be part of a sustainability assessment of biodiesel production was developed.

Chapter 3 presents the System Dynamic (SD) model of the Colombian biodiesel production system and analyzes the dimensions involved. 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 sustainability in Colombia. The primary focus of that chapter 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. Chapter 4 includes the simulation of the biodiesel production system in the Colombian context considering, initially baseline conditions, that is to say the trends and functions between 1999 and 2013 will be the same up to 2030. After, selected indicators of the baseline scenario will be modified in order to generate a sensibility analysis to define two scenarios: optimistic and

pessimistic. Finally, research findings, contributions and conclusions are presented in Chapter 5, including the theoretical and practical implications and some recommendations for future work.

As results of this work, a first article was published in *Ecological Indicators - Journal*, entitled “Biodiesel -TBL+: A new hierarchical sustainability assessment framework of PC&I for biodiesel production – Part I” (Bautista et al. 2016), and a second article was submitted to the same journal concerning the validation of sustainability assessment framework proposed in the first article. Furthermore, the results of this research were presented in three international conferences: the Inter-American and Colombian Congress of Chemical Engineering (2014)- Cartagena, Colombia, the Congress of Biorefineries for Food & Fuels Materials (2015) - Montpellier, France, and the European Congress of Chemical Engineering (2015) in Nice, France.

Chapter 1: Biodiesel-TBL+: A new hierarchical sustainability assessment framework of PC&I for biodiesel production

Introduction

Sustainability assessment of biodiesel production is a topic of increasing importance due to the interest of governments to define sovereignty strategies and diversification of their energy matrix, and to set up the impact of biofuels production. In this context, this work aims to propose a hierarchical structure of sustainability assessment that integrates dimensions of sustainable development with principles, criteria and indicators (PC&I). The method employed to establish the hierarchical structure was a comprehensive literature review, based on information search strategy and classification. About 400 documents were reviewed and 113 documents were finally selected, including laws, policy documents, certificates, directives and other normative documents and papers published in peer-reviewed journals.

The first result of the analysis was the need to strengthen identification of the sustainable development assessment, adding the political and technological dimensions to the three traditional dimensions, social, economic and environmental, studied in this kind of evaluation. The second result was the proposal of a hierarchical framework for the sustainability assessment of biodiesel production. The framework comprises five dimensions associated with sustainable development evaluation, 13 principles, 40 criteria and a set of indicators that describes each criterion. Outcomes of this work provide a foundation for further discussion of sustainability assessments for biodiesel production and its potential application in specific contexts.

1.1 Insight from previous literature

The purpose of this background on previous literature reviews is to help relevant documents enable us to underline the main research questions of the present study. Table 1-1 summarizes 16 recent documents regarding research focus, author, and number of papers reviewed, time, source and sustainable dimensions considered (social-S, economic-Ec, environmental-En, political-P and technological-T). These studies are classified through a typology reflecting the

research focus, such as: biodiesel supply chain studies, quantitative approaches (models and metrics), sustainability frameworks of criteria and indicators for bioenergy and biofuels, and sustainability initiatives (regulatory frameworks, voluntary standards/certification schemes, scorecards). With regard to the biodiesel supply chain studies, the documents show that the biomass sourcing network issues were often analysed (Van Cauwenbergh et al. 2007; Mekhilef, Siga, and Saidur 2011). The literature also shows that most of the quantitative approaches were linked to life cycle studies (Malça and Freire 2011; Cherubini and Strømman 2011) and to footprint computation tools (Cucek and Kravanja 2012).

Table 1-1. Previous literature that it was considered

Research focus	Author	Number of papers reviewed	Time	Source	Sustainable dimensions				
					S	Ec	E	P	T
Biodiesel supply chain studies	(Van Cauwenbergh et al. 2007)	25	1993-2006	EE	x	x	x		
	(Mekhilef, Siga, and Saidur 2011)	30	2006-2010	RSER		x	x		
Quantitative approaches (Models and metrics)	(Malça and Freire 2011)	28	1992-2010	RSER			x		
	(Cherubini and Strømman 2011)	45	1997-2010	BTJ			x		x
	(Cucek and Kravanja 2012)	15	2005-2011	JCP			x		
Sustainability frameworks of criteria and indicators for bioenergy and biofuels	(Cramer et al. 2007a)	8	1995-2007	Report	x		x		
	(Fao and Befsci 2007)	20	1995-2006	Report	x	x	x		
	(Buchholz, Luzadis, and Volk 2009)	12	1996-2008	JCP	x	x	x		
	(Buytaert et al. 2011)	20	1991-2010	RSER	x	x	x	x	
	(Josephine K. Musango and Brent 2011)	30	1995-2010	ESD	x	x	x		x
	(Kurka and Blackwood 2013)	41	1999-2012	RSER	x	x	x		x
	(Mata et al. 2013)	49	2003-2012	SERA	x	x	x		
	(Florin, van de Ven, and van Ittersum 2013)	50	1996-2013	ESP	x	x	x	x	
Sustainability Initiatives (regulatory frameworks, voluntary standards, certification schemes, scorecards)	(Fritsche et al. 2006)	35	1990-2006	Book	x		x		
	(FAO and BEFSCI 2011)	26	1998-2011	Report	x	x	x	x	
	(Scarlat and Dallemand 2011)	18	1999-2010	EP	x	x	x	x	

RSER-Renewable and Sustainable Energy Reviews

EE-Ecosystems and Environment

SERA-Sustainable Energy Technologies and Assessments

JCP-Journal of Cleaner Production

ESP-Environmental science and policy

ESD-Energy of Sustainable Development

EP-Energy Policy

BTJ-Bioresource Technology journal

On the other hand, holistic approaches of sustainability frameworks of criteria and indicators for bioenergy and biofuels were proposed by multiple research works; the earliest related literature review was Cramer et al. (2007a), who proposed a set of sustainability criteria and indicators about environmental and social themes. Kurka et al. (2013) also proposed criteria and indicators for bioenergy development. Buchholz et al. (2009) considered only sustainability criteria, and Musango et al. (2011) added a conceptual framework with a system dynamics approach to technology sustainability assessment. Similarly, Mata et al. (2013) proposed a sustainability analysis of biofuels through the supply chain using indicators and Florin et al. (2013) presented an indicator assessment of biofuel production systems.

Concerning sustainability initiatives (regulatory frameworks, voluntary standards, certification schemes, scorecards) proposals were linked to sustainability assessment of biofuels, including goals, principles, criteria and indicators. FAO & BEFSCI (2011) proposed a set of tools that

included classification, certification, standardization, and lifecycle assessments of biofuels. Additionally, authors identified sustainability standards for bioenergy (Fritsche et al. 2006) and a global overview about development of biofuels / bioenergy sustainability certification (Scarlat & Dallemand 2011). The sustainability initiatives had in common their sustainability objectives, but the assessment approach and metrics showed important differences, thus comprehensive integration was difficult.

From the sustainability dimensions considered by the different types of documents, the literature reviews reflect that social, economic and environmental dimensions were frequently considered. The political dimension has been taken into account by sustainability initiatives (regulatory frameworks, voluntary standards, certification schemes and scorecards). The technological dimension is mostly included in sustainability frameworks of criteria and indicators for bioenergy and biofuels.

Regarding the research focus in the previous literature reviews, and with the aim of proposing a new hierarchical sustainability assessment framework of biodiesel production, the following research questions were considered:

- Which sustainability dimensions should be part of a sustainability assessment framework?
- How is the current sustainability assessment framework structured?
- What components could be proposed for a sustainability assessment framework?

To provide an answer to these questions, this work developed a comprehensive state of the art, following a search strategy of material collection and descriptive analysis, taking the previous literature review (Table 1-1) as a starting point.

1.2 Methods

A systematic literature review method composed by a search strategy and analysis of the collected documents has been deployed. This method is described as follows:

1.2.1 Search strategy of documents

To determine the state of the art required to perform the sustainability assessment of biodiesel production, a search strategy considers: (1) defining the type of documents and keywords to

perform the search in databases, (2) establishing the sources of information to be employed (databases and organizations websites), and (3) delimiting the time interval to be explored.

(1) The type of documents to be considered includes:

- Methods, structures, systems, certifications, standards and regulatory frameworks that incorporate goals, objectives or principles, criteria and indicators, or verifiably assess the sustainability of the biodiesel production.
- Research reports, articles in journals, project reports and PhD memories about sustainable biodiesel production. Those studies should at least consider the traditional dimensions of sustainable development (social, economic and environmental).
- Research reports, articles in journals, project reports and theses about one or more stages of the biodiesel supply chain.

(2) The keywords considered for the search in databases and organizations' websites were:

- Biofuel certification, biofuels initiatives.
- Biofuel sustainability criteria and indicator.
- Biofuel standards, policies and scorecard.
- Biofuel sustainability assessment framework.

The sources of information to be employed (databases and organizations' websites):

- Academic and research institution websites.
- Websites of governmental and non-governmental institutions working on sustainability assessment of biodiesel.
- Scientific databases included in the Web of Science and Scopus, in particular the following journals' databases: American Chemical Society ACS, Science Direct, Springer Journal, and Nature.com.

(3) The period of information searching: It begins in 2000 and finishes in 2014. This was defined as the initial year of the period because a constant growth in biodiesel production at the global level as well as higher market prices were observed since 2000 (OECD and FAO 2014).

1.2.2 Descriptive document analysis and selection

The descriptive analysis of the state of the art was made with the aim to know the temporal distribution of documents determined by the set of keywords, as well as document distribution by information sources, the subject area in information sources and the sustainability assessment dimensions; also the keywords, the most recurrent by geographical regions.

Afterwards, the document selection was carried out through a deductive process, considering the three research questions of this work and the search strategy. Initially, the document must incorporate at least two of the following concepts: goals, objectives or principles, criteria, indicators or verifiable facts. After that, the document should at least consider the traditional dimensions of sustainable development (social, economic and environmental). Finally, the document should take into account the sustainability assessment framework. If the identified document in the search strategy complies with two or more previous conditions then the document is selected.

1.3 Results from the literature review

The results of the method described above are first presented through a descriptive analysis. Then the documents are selected and their classification by document type is proposed. Subsequently, the implications of the results regarding the sustainability dimensions that were defined in the present work are discussed. Finally, a discussion on the general frameworks proposed by the literature is proposed.

1.3.1 Descriptive analysis

Overall, it could be indicated that the sustainability assessment of biofuel production is a research topic that has been strongly developed in the last 10 years. This aspect is shown in Figure 1-1; in total, 411 different documents were identified. From 2003 until 2009, the number of documents increased by 50% per year. Then, from 2009 to 2014 the documents increased approximately 40%, with a significant number of documents about biofuel policies in 2013. The use of “biofuel and sustainability criteria” as a keyword presented constant growth until 2007, similar to the keyword “biofuel sustainable assessment framework”. The document’s temporal distribution showed that the keyword “biofuel certification or biofuels initiatives” (regulatory frameworks, voluntary standards/certification schemes, scorecards) was seen since 2003 and continued to be included as a keyword until 2014.

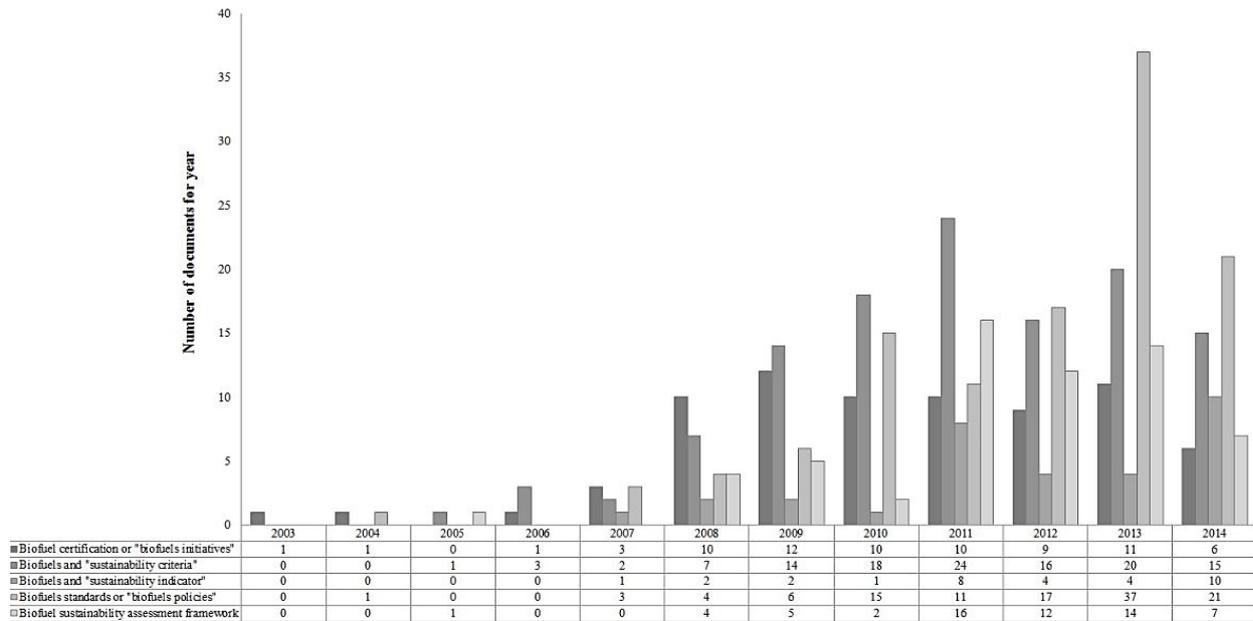


Figure 1-1. Document temporal distribution

The information sources were highly diverse, with 159 different journals and approximately 50 websites of governmental and non-governmental institutions being identified. The information sources with the most number of documents published are shown in Figure 1-2. The journal *Energy Policy* and the institutions' websites were highlighted regarding the keyword "biofuels standards or biofuels policies". The keyword "biofuels and sustainability criteria" also had a significant number of documents published in the journal *Biofuels, Bioproducts and Biorefining*. Furthermore, the institutional website show a high number of documents related to models of biofuels' certification and sustainable initiatives, because these institutions promote and in some case grant certification adopted by biofuels supply chain stakeholders. Regarding to energy, biofuels and policy journals, the keyword resulting in the highest number of documents was *biofuels standards*. As a consequence, the influence of standards and policies on the promotion of sustainable biofuels production has been extensively analyzed by peer reviewed scientific documents.

Figure 1-3 shows the documents' distribution by "subject area". The subject areas applied in this work were selected taking into account the abstract and citation database Scopus, which has a coverage span of 27 subject areas. Thus, each identified document was linked to a subject area, and the subject areas were associated with the sustainability dimensions used in previous literature reviews for biofuel assessment (refer Table 1). The subject areas having the highest number of related documents are those of the environmental dimension: energy, environmental science, agricultural biological science, chemical engineering and engineering. Moreover, the sustainability assessment dimensions with significant subject areas and documents published

were environmental and technology dimensions, while a moderate number of subject areas and documents were found for economic and social dimensions. The lowest number was found for the political dimension. It is interesting to observe that the keywords *biofuel standards* or *biofuel policies* obtained a high number of documents published in the subject areas energy and environmental sciences.

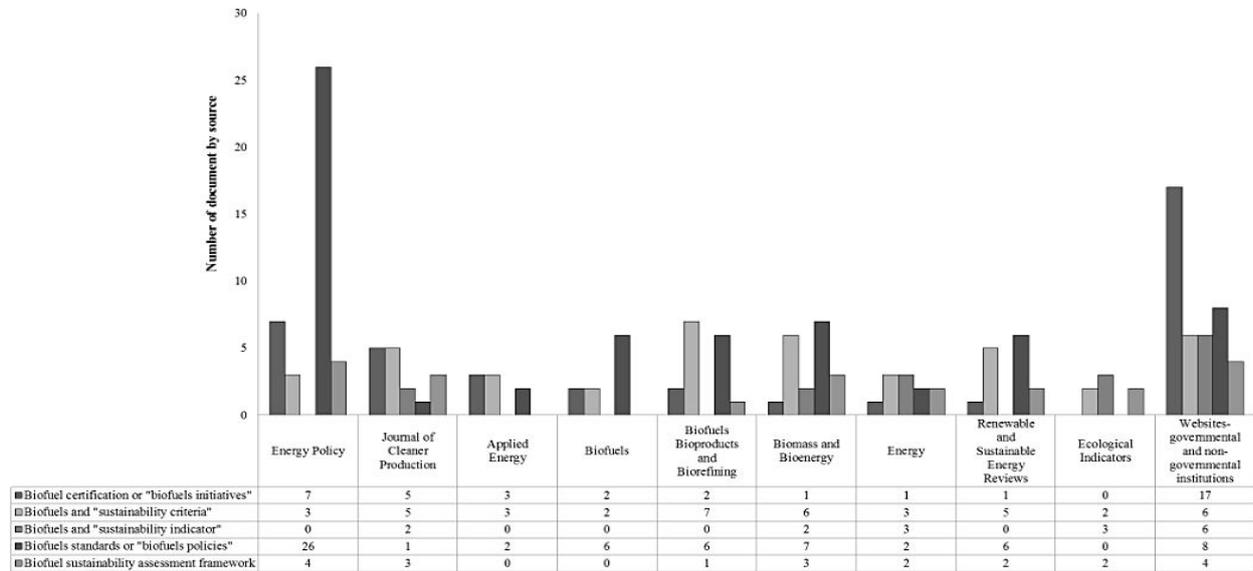


Figure 1-2. Distribution of document in the information sources

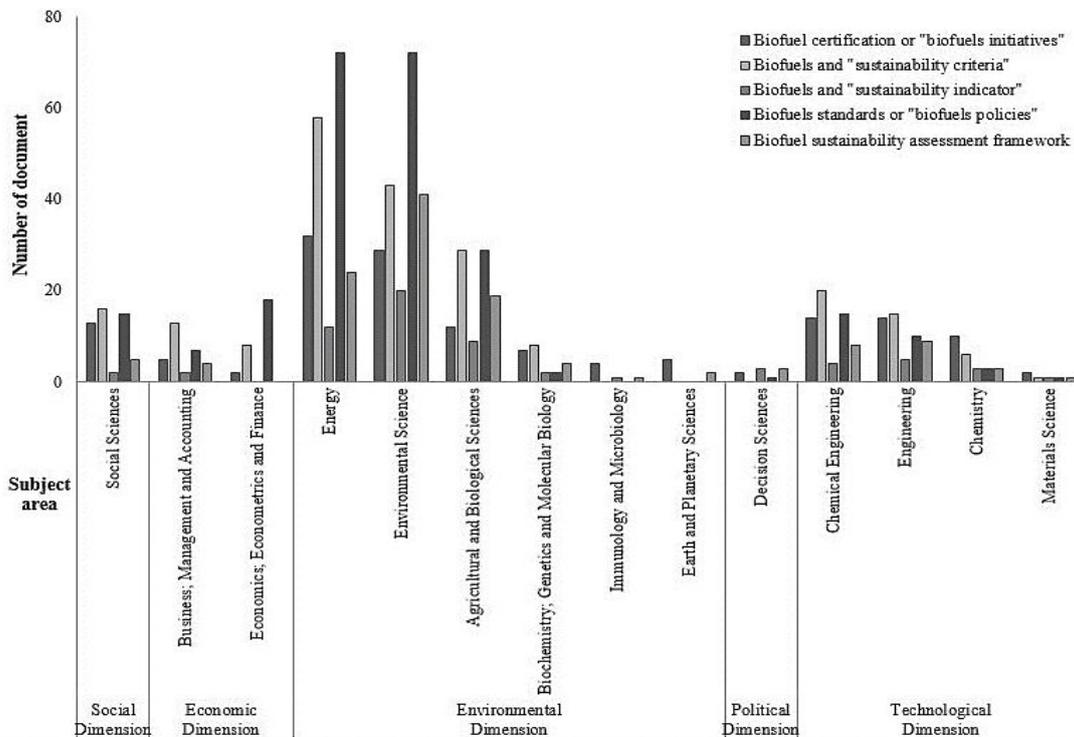


Figure 1-3. Documents by subject area

To conclude, the geographical distribution of documents by region shows that Europe was the region with the highest number of publications from 2003 to 2014. The most relevant keyword

was “biofuels and sustainability criteria”. For the second region, North America (United States and Canada), and the third region, Asia, the relevant keyword was “biofuels standards and biofuels policies”. The fourth region was Latin America, with a similar number of documents in the five keywords (refer Figure 1-4). It was highlighted that the European region and the United States are the principal biofuel producers and consumers, and the Asian – Latin American regions are the important potential expansion areas for biofuel production (EIA 2011).

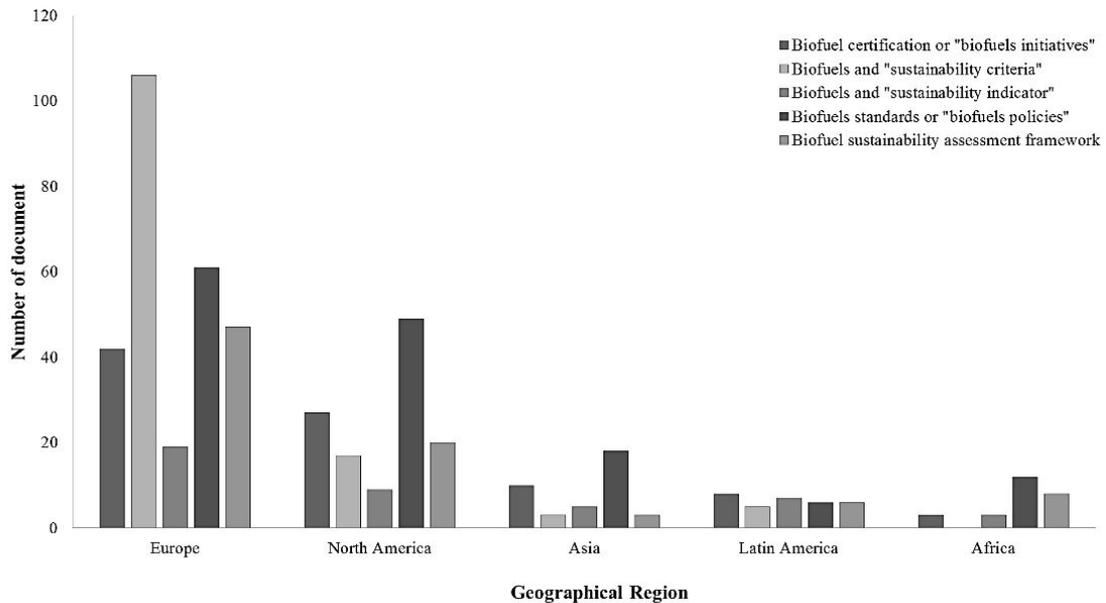


Figure 1-4. Geographical distribution of documents

1.3.2 Information Classification

As a result of the selection process described in section 1.2.2, 113 documents met the selection conditions and were classified in four groups according to the type of documents. The first group includes biofuel certification standards and sustainability initiatives (regulatory frameworks, voluntary standards/certification schemes, scorecards). The second group corresponds to documents where biofuel sustainability criteria and indicators were presented. The third group corresponds to biofuel standards and policies that aim at sustainability of the biofuel production chain and its stakeholders. Finally, the fourth group contains documents about biofuel testing frameworks and scorecards. The selected documents and their classifications are shown in Table 1-2.

Table 1-2 Classification of selected documents

Groups	Selected Documents	
Certification and initiatives of sustainability	1. Bonsucro, Better Sugarcane Initiative. 2. FLO, Fair Trade, Fairtrade Labelling Organizations International 3. GQA, Genesis Quality Assurance	20. SAN/RA, Sustainable Agriculture Network/Rainforest Alliance 21. Sustainability criteria and indicators for bioenergy developed by FBOMS

Groups	Selected Documents		
criteria of biofuels	<ol style="list-style-type: none"> 4. PEFC, Program for the Endorsement of Forest Certification schemes 5. RTRS, Roundtable for Responsible Soy Production 6. GGLS2, Green Gold Label 2. Agriculture Source Criteria 7. Nordic Eco-labelling of Fuels 8. UNCTAD Biofuels Initiative, 2006 9. Certification by the standardization institute NEN and the Rotterdam Climate Initiative (RCI) to assess the sustainability requirements for solid, liquid and gaseous biomass for energy application and transport fuels, Netherlands, 2011 10. RTFC, Renewable Transport Fuel Certificate 11. BLE, Sustainable Biomass Production. Germany 12. EcoLogoM, has criteria for renewable energy sources with specific criteria for biomass and biogas, Canada, 1988 13. LEI, the Lembaga Ekolabel Indonesia, 2005 14. MTCC, the Malaysian Timber Certification Council, 2005 15. RSPO, Roundtable on Sustainable Palm Oil, 2007 16. ELECTRABEL Label Green. Development of ecological standards for biomass in the framework of green electricity labelling. Belgian regions, 2006. 17. EUGENE (EU), Project Focus on end part of chain. Actual label, adds extra principles for biomass in specific. 18. Social Fuel seal – Brazil 19. Southern African NGO position on Biofuels 22. Summary IATP Sustainable Biomass Production Principles & Practices 23. ACCS, Assured Combinable Crops Scheme 24. CSBP, Council on Sustainable Biomass Production, the United States. 25. NTA 8080, Sustainable Production of Biomass—The Netherlands 26. FSC, Forest Stewardship Council 27. GAP, Global Partnership for Good Agricultural Practice 28. IFOAM, International Federation of Organic Agriculture Movements 29. LEAF, Linking Environment and Farming 30. SAI, Social Accountability International 31. Sustainability 32. Guide in Biomass Production and Processing in the Biofuel chain in Colombia 33. ISO 26000 – Responsibility social. 34. ISO 14040 - Life Cycle Assessment 35. GBEP, Global Bioenergy Partnership, 2005 36. UNEP, 2009. Towards Sustainable Production and 37. Use of Resources: Assessing Biofuels 38. USAID, Biofuels in Asia: an analysis of sustainability options. United States Agency for International Development. 39. RSB, Roundtable on Sustainable Biofuels, established by the Ecole Polytechnique Fédérale de Lausanne (EPFL) Energy Center in 2006 40. Pilot Testing of GBEP Sustainability Indicators for Bioenergy in Colombia (FAO 2014). 41. ISCC, International Sustainability and Carbon Certification 		
Biofuels standards and policies	<ol style="list-style-type: none"> 1. RTFO, Renewable Transport Fuel Obligation – UK 2. CAP, Common Agricultural Policy 3. Directive 2009/28/EC of the European Union, directive on renewable energy. 4. BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation 5. BioNa Dv, Biomass Sustainability order, Germany 6. Biodiesel standard, ASTM D6751 and the EU's EN. 14214:2003 7. ASTM D6751 was drafted for Biodiesel fuel blends. 8. RFS2, Renewable Fuel Standard, the United States, 2010 9. WTO rules and principles (UN 2008) 10. LCFS, Low Carbon Fuel Standard (LCFS), required by California, United States. 11. SBA, Sustainable Biodiesel Alliance, in the United States, 2009 12. RFQD, Revised Fuel Quality Directive of the European Union, 2008 		
Papers published in peer-reviewed journals	<ol style="list-style-type: none"> 1. (Florin, van de Ven, and van Ittersum 2013) 2. (Brent and Musango 2013) ; 3. (Kurka and Blackwood 2013); 4. (Pesqueira and Glasbergen 2013); 5. (FAO 2013); 6. (Elibehri, Segerstedt, and Liu 2013); 7. (Mangoyana, Smith, and Simpson 2013); 8. (Milazzo et al. 2013); 9. (German and Schoneveld 2012); 10. (BID and MME 2012a) 11. (Josephine K. Musango et al. 2012); 12. (FAO & BEFSCI 2012) ; 13. (Scarlat and Dallemard 2011); 14. (Halog and Manik 2011); 15. (McBride et al. 2011) 22. (Gnansounou et al. 2009) 23. (Edgard Gnansounou 2011) 24. (Oviedo, S; Narvaez, P; Camargo, M; Morel, L;Forradellas 2011) 25. (S. Zapata, Franco, and Dyer 2011) 26. (World Energy Council 2010) 27. (Boons and Mendoza 2010) 28. (Markevičius et al. 2010) 29. (Lendle and Schaus 2010) 30. (Hoon and Gan 2010) 31. (J. Van Dam, Junginger, and Faaij 2010) 32. (Buchholz, Luzadis, and Volk 2009) 33. (Brent 2009) 34. (Delzeit and Holm-Müller 2009) 41. (EC and BTG 2008) 42. (Dehue et al.) 43. (Cramer et al. 2007a) 44. (FAO and BEFSCI 2007) 45. (Allen 2007) 46. (Van Cauwenbergh et al. 2007) 47. (Bantz and Deaton 2006) 48. (Moret, Rodrigues, and Ortiz 2006) 49. (Fritsche et al. 2006) 50. (Oehme 2006) 51. (Lewandowski and Faaij 2006) 52. (Clark and Macquarrie 2002) 53. (Nrtee 1999) 		

Groups	Selected Documents		
	16. (FAO and BEFSCI 2011) 17. (Vaccaro et al. 2010) 18. (Amigun, Musango, and Brent 2011) 19. (Pruyt and Sitter 2008) 20. (Kim, Kim, and Dale 2009) 21. (Szarka et al. 2008)	35. (Franco and Flórez 2009) 36. (Groom, Gray, and Townsend 2008) 37. (Jinke van Dam et al. 2008) 38. (Nations 2008) 39. (Timilsina and Shrestha 2011) 40. (Cavalett and Ortega 2010)	54. (Mendoza et al. 1999) 55. (Bueren and Blom 1996) 56. (Timilsina and Shrestha 2011) 57. (Gudmundsson 2008)
Testing Framework & scorecard	1. Inter-American Development Bank Sustainability Scorecard 2. World Bank/WWF Biofuels environmental sustainability scorecard 3. Sustainability Assessment Framework (de Lange and Wolvekamp 2006)		

As may be seen from Figure 1-5, the greatest number of studies corresponds to papers published in peer-reviewed journals, 45% of these studies. The second proportion, 40%, was obtained by certification and initiatives of sustainability criteria of biofuels. The third are biofuel standards and policies, at 12% of the studies. The fourth, 3% of the studies, are testing frameworks and biofuel scorecards carried out by governmental and non-governmental organizations.

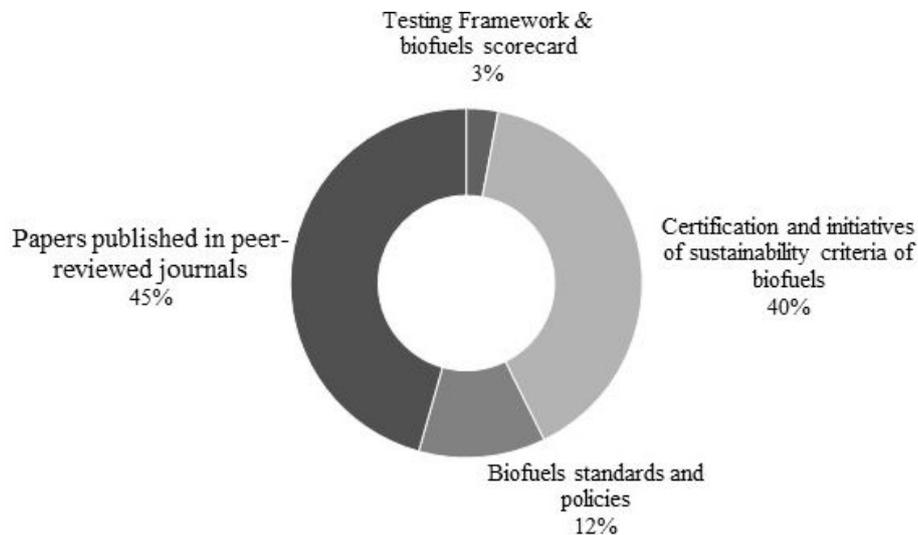


Figure 1-5. Percentages of document by classification group of documents.

Comparing the document temporal distribution (Figure 1-1), the distribution of documents by information source (Figure 1-2) and the document by subject area (Figure 1-3), it is observed in Figure 1-5 that there is a parallel trend of research made by scientific community through peer-reviewed journals (Figure 1-1 and 1-3) and the research application by means of certification and voluntary initiatives of sustainable biofuels production promoted by Government and non-governmental organizations or institutions (websites in Figure 1-2). This trend is positive because the scientific research can strengthen the certification processes and vice versa.

Regarding the 113 selected documents, a set of criteria and indicators was identified and a number of documents were associated with each criterion (refer Appendix 1). The more cited criteria are those of the environmental dimension, mainly associated with assessment of

greenhouse gas emissions, air quality, water quality and quantity, and waste management. Second, the criteria of the social dimension related to aspects of rural development, compliance with labour laws, and food security. Taking third place in citations are criteria of the political dimension in areas such as compliance with local laws, ethics and transparency. Those criteria with lower levels of document citation were those associated with economic aspects such as influence on the production volume of first-generation biodiesel (from edible feedstock) of the oil market and advanced biodiesel. Criteria belonging to the technological dimension are those that obtained the lower number of citations (refer Figure 1-6).

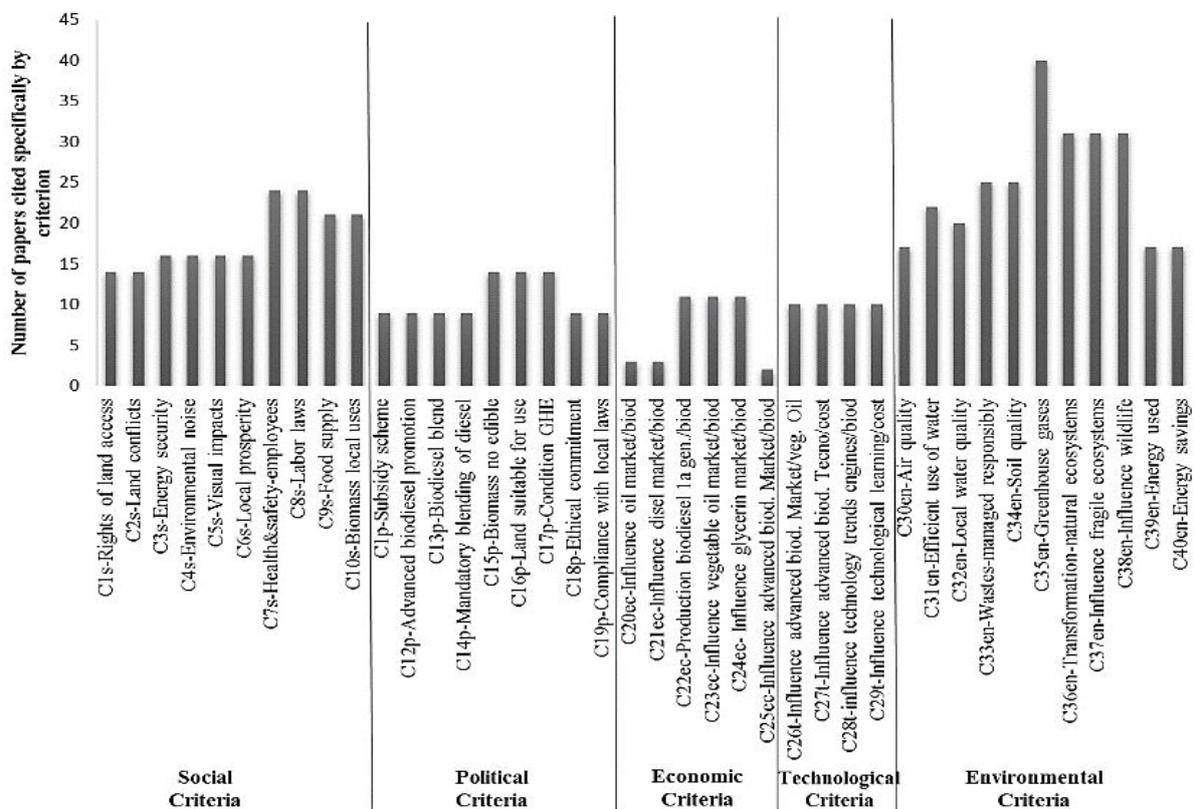


Figure 1-6. Number of papers cited specifically by criterion.

1.3.3 Sustainability assessment dimensions

The adoption of sustainability assessment should implement a holistic perspective by comprehensively/simultaneously/equally considering the relevant/full range of ‘dimensions’, since decision-makers and other stakeholders wish to be informed of the full spectrum of impact. Associated with sustainability assessment, the environmental, social and economic dimensions are sometimes referred to as the ‘three pillars’ of sustainability or the ‘triple bottom-lines – TBL’ (Hacking and Guthrie 2008). The TBL is an approach which encompasses the three dimensions of sustainability and is linked to the strong theoretical fit for measuring

multidimensionality of sustainability. These dimensions should be treated differently but eventually integrated. Sustainability can be achieved by a systematically linked “socio-economic-environmental system” and not by a single component (Lee et al. 2012a).

According to the sustainability dimensions studied, 43% of the selected documents were related to the environmental dimension, 29% to social dimensions and 16% to the economic dimension. Additionally, 7% and 5% of the documents perform political or technological assessments, respectively. Based on that behaviour, it deemed necessary to add the last two dimensions to the traditional TBL sustainability assessment.

In particular for biodiesel production assessment, the political dimension is highly relevant because the Government’s policies are essential to promote the biodiesel production, creating economic conditions and favorable markets such as subsidies, tax exemptions, and biodiesel compulsory consumption as a diesel mixture. Moreover, the technological dimension is also relevant in the sustainability assessment of biodiesel, taking into account that emerging technologies are competing with the first generation biodiesel. Furthermore, the incorporation of political and technological dimension adds additional challenges to sustainability assessment associated with maturity indicators. The political and technological indicators do not have the similar maturity as the economic or environmental indicators, for this reason, the assessment framework proposed in this work will be validated through expert consultation.

The inclusion of the political dimension in sustainability assessment, it makes it possible to perform an analysis on the impact of the implementation of local or international regulatory frameworks, mandatory or voluntary biofuel certification systems, and the impact on the social, economic and environmental dimensions (Schade and Wiesenthal 2011). For example, the manner in which direct policy controls, such as renewable fuel standards and mandatory blending, increase the demand for biodiesel, which generates growth of biodiesel processors, increasing the demand of cultivation land for raw materials, changes in the ownership of land, impacts on rural employment and changes in the quality of life and living conditions of communities associated with the biodiesel production system.

The inclusion of the technological dimension permits the analysis of the influence of new technological developments on the sustainability of the biodiesel supply chain. Some examples of new technological trends are the use of non-edible vegetable oils as raw materials, the implementation of intensified production technologies, the production of non-ester biodiesel and changes in the internal combustion engine (Mohr and Raman 2013; de Wit et al. 2010).

Those aspects are fundamental for assessing the impact of implementing such technology trends on environmental and social impacts. For example, including the technological dimension could help 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. This also takes into account that the use of food crops and oils for producing fuel was promoted, the “food vs. fuel” conflict and concerns about the negative impacts of monocultures for first generation biofuels on biodiversity and water conservation especially linked to the conversion of natural terrestrial ecosystems, respectively.

This research proposes to integrate the political and technological dimensions into the three traditional sustainability dimensions (environmental, social and economic), with the aim of strengthening the multidimensional sustainability assessment. The approach covers five dimensions and was named Triple Bottom Line Extended (TBL+).

1.3.4 Frameworks previously used for sustainability assessment of biofuels

According to the state of the art, three different types of frameworks to perform the sustainability assessment of biodiesel have been identified. These frameworks are shown in Figure 1-7. Scheme 1 shown a set of principles which are described by a number of criteria. Each criterion has a set of indicators that are calculated using verifiers. Principles are ‘universal’ basic facts or attributes of a sustainable system (Florin, van de Ven, and van Ittersum 2013). A criterion is a translation of the principle into concrete requirements that have to be met (Cramer et al. 2007b). Indicators are the concrete and quantifiable aspects that will be used in the evaluation procedure (Fao and Befsci 2007). The verifiers provide additional data or information that enhances the specificity of the ease of assessment of an indicator (Buytaert et al. 2011). Sometimes verifiers are defined to double-check the indicators (E. C. EC and BTG 2008) and are also needed for indicator assessment and the control of the fulfilment of sustainability criteria (Lewandowski and Faaij 2006).

Scheme 2, in Figure 1-7, is commonly used in international certification systems and defines a set of standards which are assessed by criteria; each criterion has a set of indicators (Jinke van Dam et al. 2008). The standards are meant as basic principles for defining the “rules” which sustainable bioenergy development should follow (Fritsche et al. 2006). At the same time, the standards are a set of predetermined requirements that are assessed in certification processes

(Scarlat 2011). The definition of criteria and indicators in Scheme 2 are the same as those referred to above.

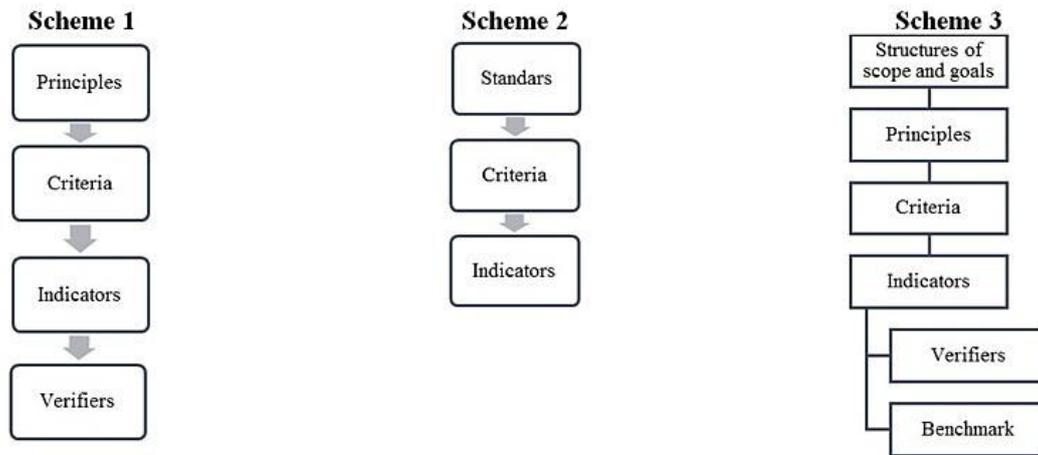


Figure 1-7. General frameworks employed to perform the sustainability assessment of biodiesel

Scheme 3 is generally used in life cycle assessment - LCA; initially the organizational set-up needs to be established through goal and scope definitions, taking the stakeholders into account. The goal and scope definition is the phase in which the initial choices which determine the working plan of the entire LCA are made. The goal of the study is formulated in terms of the exact question, target audience and intended application. The scope of the study is defined in terms of temporal, geographical and technological coverage, and the level of sophistication of the study in relation to its goal (Guinée and Tukker 2002). Each goal is described by principles and the principles are described by a set of criteria, likewise the criteria by a number of indicators. Each indicator is measured by verifiers, or judged through standards or references called benchmarks (Jinke van Dam et al. 2008).

The three schemes described are mutually complimentary, as all of them are related to principles, criteria and indicators (PC&I). However, some features of each scheme must be highlighted in order to apply them to the biodiesel supply chain:

- The first scheme allows proposing PC&I, to give a general framework of diagnostic and analysis for a specific case. A comprehensive analysis must be carried out in order to identify those criteria and indicators.
- In the second scheme, certifications define standards as minimal requirements, and the biofuels supply chain stakeholders fix the criteria and indicators that must be evaluated based on those standards.
- In third scheme, related to LCA analysis, it is required extensive and detailed information (databases of indicators) to quantify the impact of biofuel production chain

on sustainability dimensions. Then, the PC&I are defined based on the resulting impacts.

Regarding the previous considerations, the assessment framework of PC&I proposed in this work is developed in the context of the first scheme. From our point of view, it will constitute a starting point for future reflections and proposals about standards, certifications and life cycle analysis of the biodiesel sector.

1.4 The Triple Bottom Line Extended (Biodiesel-TBL+), a new framework for biodiesel sustainability assessment

The framework was constituted by *principles, criteria and indicators (PC&I)*, and has a structure of three levels, which is presented subsequently in Figure 1-8. The concepts presented in Table 1-3 were the input to determine the following definitions used in this chapter:

- *Principles*: The premises, bases or universal principles that define the sustainability of a biodiesel supply chain.
- *Criteria*: Those measurable conditions (qualitative or quantitative) that establish the level of application of the principles of a sustainable biodiesel supply chain.
- *Indicators*: are observable qualitative or quantitative expressions, which can describe the characteristics, behaviours or phenomena of reality through the development of one or more variables.

Table 1-3. Definitions of principles, criteria and indicators

PRINCIPLES	CRITERIA	INDICATORS	REFERENCES
Fundamental truth or law as the basis of reasoning or action. Principles justify the chosen criteria, indicators and verifiers	Principle or standard that a thing is judged by. Criteria enhance the meaning and operability of principles, however do not measure performance.	Used to infer the status of a particular criterion. Indicators are comprised of specific information about a criterion.	(Kurka and Blackwood 2013)
Principles are 'universal' basic truths or attributes of a sustainable system.	Criteria are the rules that govern judgment on outcomes from the system.	Means of assessing performance against criteria.	(Florin, van de Ven, and van Ittersum 2013)
Principles are usually established as general starting points that describe the objective of certification.	These objectives are then translated into measurable requirements by criteria.	Testing then utilizes indicators or verifiers, which serve as quantitative or qualitative minimum requirements for certification.	(Nations 2008)
Principles are general conditions for achieving sustainability (which is the ultimate goal).	Criteria are specific objectives, more concrete than principles and relating to a state of the system, and therefore easier to assess and to link indicators.	Indicators are variables of any type that can be assessed in order to measure compliance with a criterion.	(Van Cauwenbergh et al. 2007)
A principle is the general starting point as a basis for the quality requirements.	A criterion is a translation of the principle into concrete requirements that have to be complied with.	An indicator is a qualitative or quantitative parameter, by which a criterion becomes testable. Indicators must be clear and verifiable.	(Cramer et al. 2007b)
The principles are the overarching ideas or concepts that the standard tries to aim at.	The criteria are the particular aspects that one operator has to follow in order to apply the principle.	Indicators are the concrete verifiable and quantifiable aspects that are used in the evaluation procedure.	(Fao and Befsci 2007)

PRINCIPLES	CRITERIA	INDICATORS	REFERENCES
A fundamental truth or law as the basis of reasoning or action. They provide the justification for Criteria, Indicators and Verifiers.	A Criterion can be one that adds meaning and operationally to a principle without itself being a direct measure of performance.	An indicator is any variable or component of a system used to infer the status of a particular Criterion. Indicators should convey a 'single meaningful message'. This 'single message' is termed information.	(Mendoza et al. 1999)
A principle is a fundamental law or rule, serving as a basis for reasoning and action. Principles are explicit elements of a goal.	A criterion is a state or aspect of the dynamic process of a system, which should be in place as a result of adherence to a principle.	An indicator is a quantitative or qualitative parameter, which can be assessed in relation to a criterion. It describes in an objectively verifiable and unambiguous way features of the system.	(Bueren and Blom 1996)

The first level in the framework was the interaction between the five dimensions of the sustainability Triple Bottom Line extended (Biodiesel-TBL+) and the biodiesel supply chain stages. In this interaction, the sustainability principles were defined. The principal stages of the supply chain considered were: feedstock plantation, storage facilities, oil extraction plants, biorefineries (feedstock transformation), biodiesel-diesel blending facilities and retail outlets (RS 2008; Kumar and Nigmatullin 2011; Andersen et al. 2012; Avami 2012; Awudu and Zhang 2012; Mata et al. 2013).

The second level was made up of a set of sustainability assessment criteria linked to each principle. These criteria were identified as a measurable condition (qualitative or quantitative) aiming to assess how the sustainability principle was applied to the biodiesel supply chain. The first and the second level in the framework were defined in order to make a general sustainability assessment. Therefore, the principles and criteria can be applied regardless of the economic, social, political or biogeographic context, the technological conditions or the raw materials used, among other aspects.

Finally, in the third level, indicators were established to evaluate the characteristics or behaviours of each criterion. Besides principles, and criteria, the indicators must refer to particular conditions of the biodiesel production system, or the assessment scale (national, regional, local). Therefore, the framework could be applicable to specific contexts. The new framework was summarized in Figure 1-8.

As outlined earlier, the biodiesel sustainability framework proposed covers five dimensions (Triple Bottom Line Extended-TBL+). The two additional sustainability dimensions (political and technological) were included with the aim to increased level of granularity and visibility of the principles, criteria and indicators (PC&I).

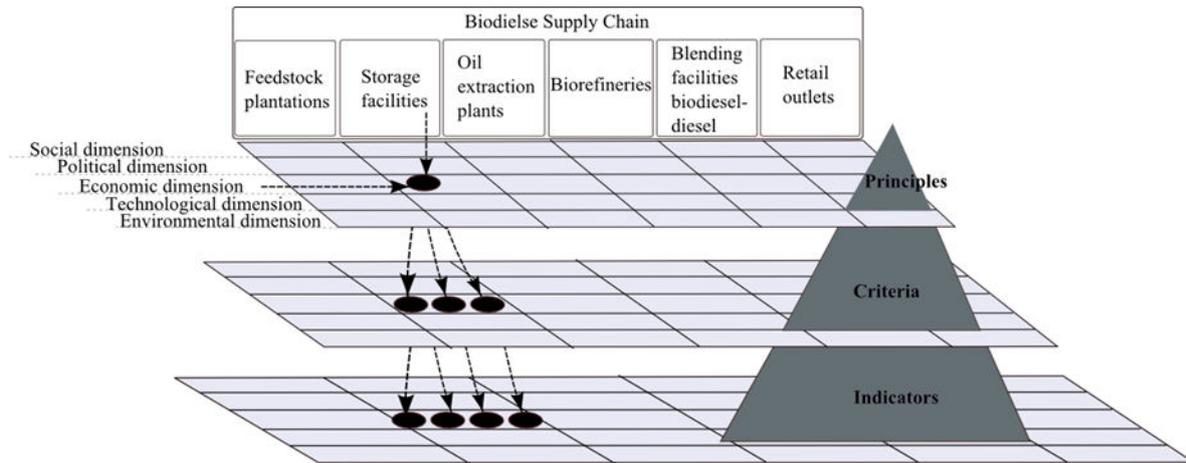


Figure 1-8. Biodiesel sustainability framework (Bautista et al. 2016).

1.5 Application of the new assessment framework to biodiesel production

The new framework proposed was applied to the biodiesel production system. Overall, 13 principles and 40 criteria were identified through the analysis of 113 documents selected, and their description is presented in Figures 9 to 13. Each indicator is described in Appendix 1, where references linked to each dimension are also shown there. The topics considered in the social dimension include as principles the respect of the property land rights, the social acceptability, the promotion to responsible work condition and prevention of food supply alteration. The criteria are defined to assess the conflict level that can generate the raw materials cultivation and the biodiesel production on communities. Additionally, the criteria permits to analyze the conflicts change with respect to access and tenure land, the community and workers life conditions, and their influence on social acceptability of the biodiesel production. The social principles and criteria, and its indicators are described in Figure 1-9 and in Appendix 1, respectively.

The principles in political dimension are referred to the influence of national and international policies about promotion, market, and sustainable production. The political criteria seek assess the agreement between national and international subsidies schemes, advanced biodiesel production and biodiesel– diesel blended, national capability in biodiesel research and development. Also, it includes the raw material production consistent with international environmental policies, and local perception on ethical and transparency commitment by the actors in the biodiesel production system. The political principle and criteria are described in Figure 1-10, and the indicator in Appendix 1.

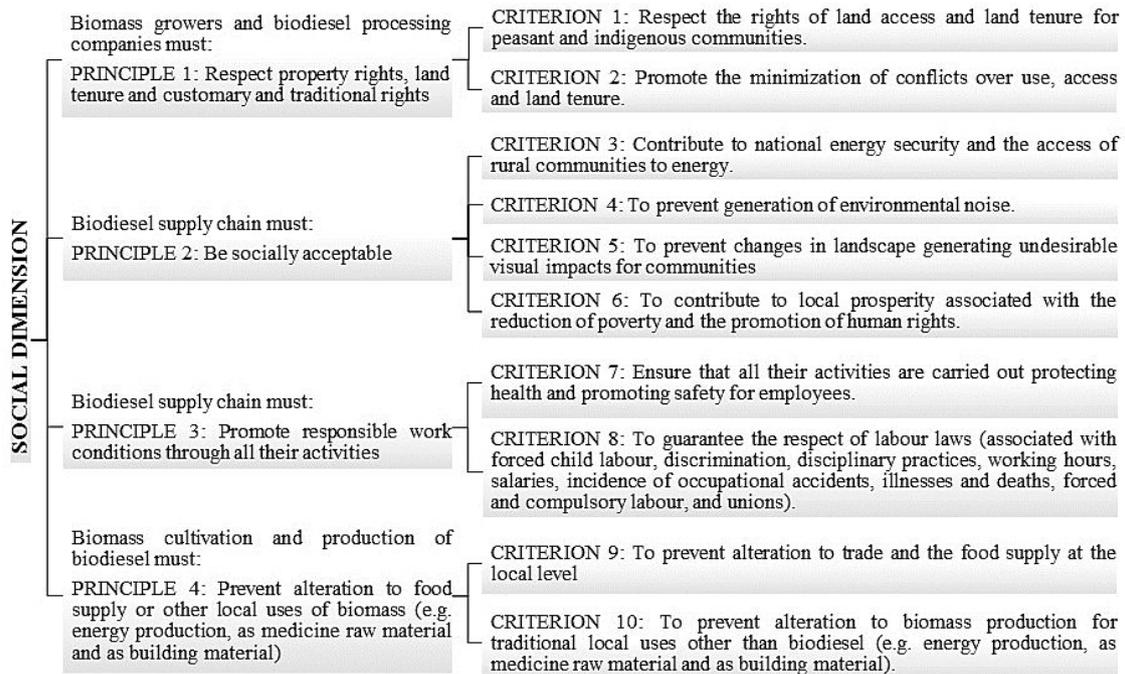


Figure 1-9. Social dimension: principles and criteria

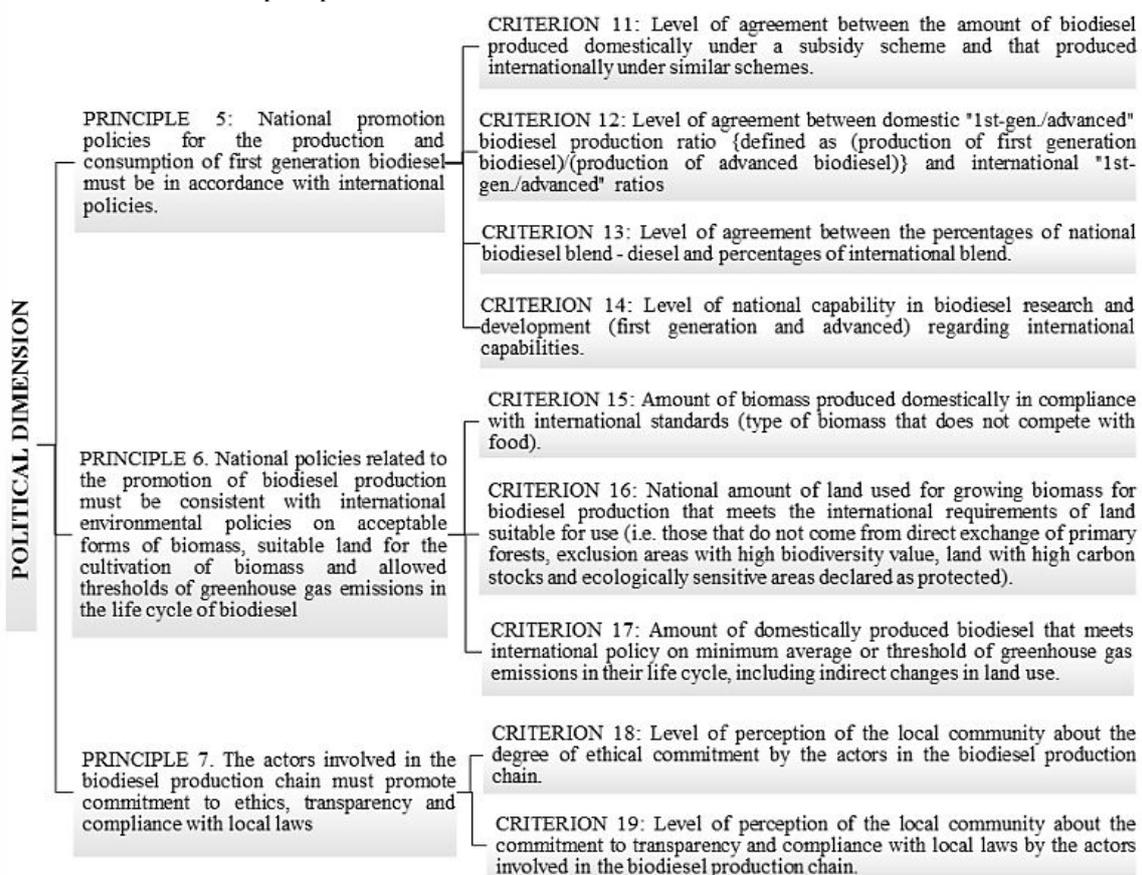


Figure 1-10. Political dimension: principles and criteria

Economic principle underline that the biodiesel production must be sustainable at both macroeconomic and microeconomic level. The second level, economic criteria assess the influence level of macroeconomic variables as oil market, diesel market, first, second and third

generation biodiesel market, on microeconomic variables as vegetable oil price, biodiesel price and glycerol price. The economic principle and criteria are described in Figure 1-11. The indicators are presented in Appendix 1.

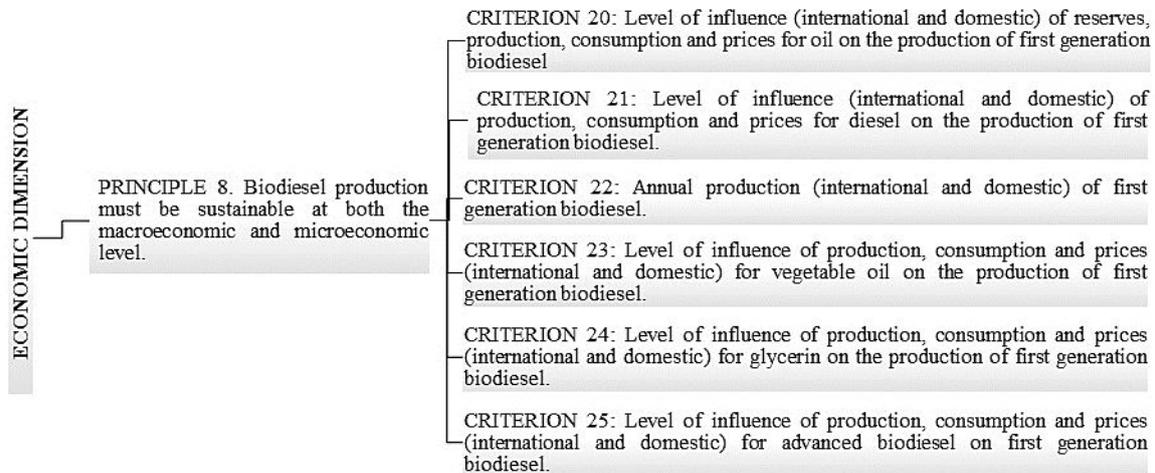


Figure 1-11. Economic dimension: principles and criteria

The technological principle is focused in the reduction of negative impact on environment and the efficiency and cost reduction. The criteria taking into account the influence of emerging technologies for first, second and third biodiesel production on the demand of natural resources, pollution generation, and cost reduction. Also, the criteria consider the technological learning in the first generation biodiesel linked to technological improvements and cost reduction. The technologic principles and criteria are described in Figure 1-12. The indicators are described in Annex 1.

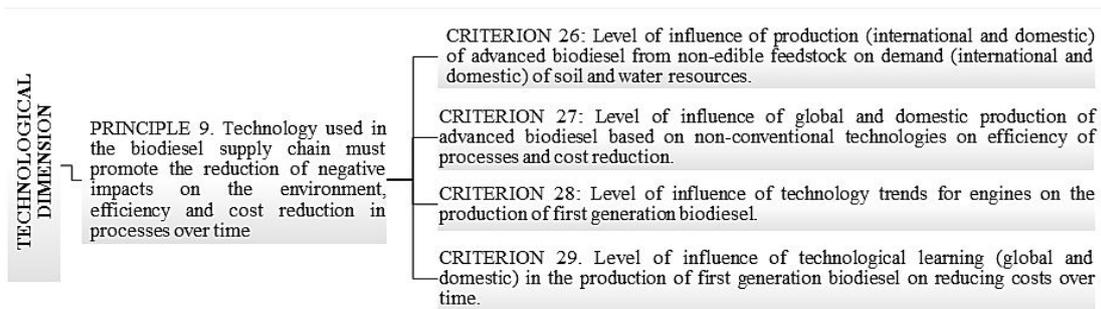


Figure 1-12. Technological dimension: principles and criteria

The environmental principles consider issues as air, soil and water quality, waste and wastewater management, balance of greenhouse gas, conservation and protection of biodiversity and wildlife, and energy efficiency. In general, the environmental criteria assess the influence of biodiesel supply chain on the environmental condition, the transformation of natural ecosystem and the quality of natural resources. The environmental principle and criteria are described in Figure 1-13. The indicators are presented in Appendix 1.

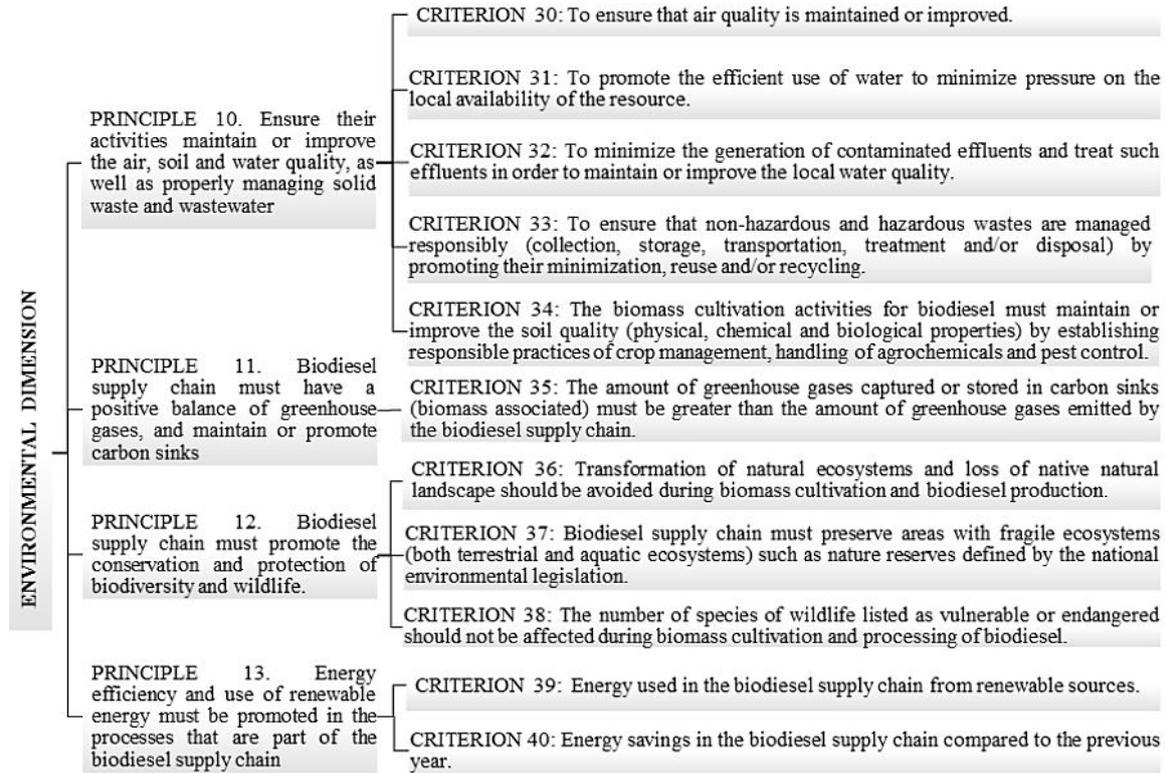


Figure 1-13. Environmental dimension: principles and criteria

1.6 Discussions

When the new framework for biodiesel sustainability assessment was compared with other similar studies (Bueren and Blom 1996; Mendoza et al. 1999; Fao and Befsci 2007; Cramer et al. 2007a; Van Cauwenbergh et al. 2007; Florin, van de Ven, and van Ittersum 2013; Kurka and Blackwood 2013), significant differences were found. First, the new framework considered five dimensions in the sustainability assessment, in particular the technological dimension, compared with the three traditional dimensions. Second, it was proposed the integration between the sustainability assessment dimensions with the biodiesel supply chain. Third, the relations between the levels of hierarchical structure, that is, each sustainability dimension was assessed by way of a set of principles; likewise, each principle was assessed by a set of criteria and each criterion by a set of indicators. Taking into account the points above, the new framework was comprehensive at both the principle and criteria levels, while also being adaptable to different contexts and biofuel supply chains at the indicator level.

The present research also compared the new framework with works about assessment tools for sustainable biofuel production, such as the proposal by (Silva Lora et al. 2011; Buytaert et al. 2011; FAO and BEFSCI 2012; Cucek and Kravanja 2012). These works describe the performance and applicability of an existing selection of tools that are potentially useful for

sustainability assessment of bioenergy systems, but do not propose an assessment hierarchical framework.

Another type of sustainability assessments are those conducted on the basis of the life cycle assessment, for example methodology for the PROspective SUstaInability assessment of TEchnologies - PROSUTE (Gaasbeek and Meijer 2013), Impact assessment methodology of Leiden University, and Eco-indicator 99 (Goedkoop and Spriensma 2001). These assessment proposals set out impacts categories about social, economic and environmental aspects. The impacts are quantified, and normalized by category and as a result give a sustainability level. The proposed PC&I framework in this work can be strengthened by the assessment methods above mentioned, especially at the level of indicators. Also, the proposed PC&I framework could contribute to sustainability assessment based in life cycle assessment.

Regarding the conditions for applying the proposed assessment framework, three aspects were identified. First, the advanced biodiesel production assessment should consider the influence of substitute renewable energy production. Second, it must take into account the local climate change influence on the indicator assessment definition. Finally, the third aspect, the adaptation of the framework to a specific context needs a biodiesel production system stakeholder's participatory consultation to define the set of indicators to be considered.

In other regards, when looking at the new framework's structure, in particular the amount of proposed principles and criteria by dimension, it could be underlined that a larger quantity of those were related to principles of environmental and social dimensions (refer Figure 1-14).

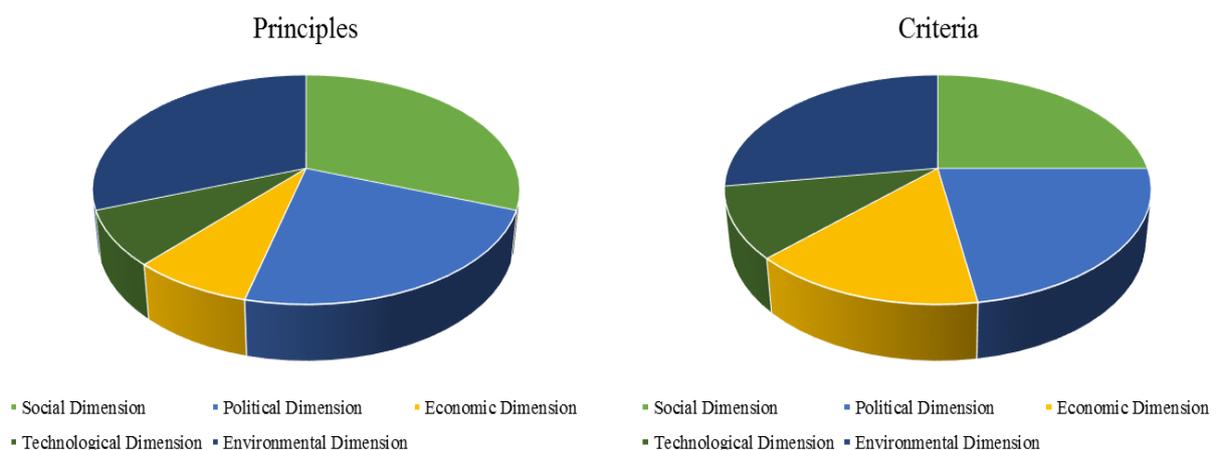


Figure 1-14. Number of principles and criteria by sustainable development dimensions TBL+

This point could be associated with the fact that social, environmental and economic dimensions are traditionally studied in sustainability assessment, such as in Buchholz et al., (2009), Kurka

(2013) and Cramer et al., (2007b). In contrast, political and technological dimensions are less linked to sustainability assessments, and in general, the political and technological principles and criteria were associated with economic or social dimensions. In this context, it is suggested that further research needs to be undertaken to define a larger set of assessment criteria related to technological and political issues of biodiesel sustainability.

Another point of discussion regarding the state of the art is the manner in which academic and research institutions, as well as governmental and non-governmental institutions, apply the definition of principles and criteria to the environmental sustainability assessment of biodiesel. In general, the social and political criteria do not exemplify or consider the method of quantifying them. In addition, the political criteria do not show the influence of political contexts (macro, meso, and micro) on the sustainability assessment. Also, political and social criteria as traditionally proposed do not provide tools to analyse the level of reactivity, pro-activity or adaptability that local policies have in regard to recent directives or trends in biodiesel consuming countries. This work considers that the lack of quantification of political and social criteria might make them less comprehensible. Additionally, the difficulty of measuring political and social criteria is quite high due to the lack of formalization of links between the well-being of communities and local and international political policies, as well as economic, environmental and technological criteria.

In the case of the economic and environmental criteria, a relevant point is that these are usually described using measurement units or quantifiable factors. As a weakness of the current frameworks, it was not evident how the economic and environmental criteria are linked with the influence of advanced technologies in biodiesel production or changes in raw materials. Moreover, how the influence of governmental biofuel policies or social acceptability is on the economic and environmental criteria has not been enough clarified. Regarding the technological criteria, there are criteria associated with the efficiency of transformation processes and the technical feasibility of technologies implemented, but a lack of criteria that link the efficiency and the technical feasibility with the environmental and social impacts of the biodiesel supply chain. Finally, the relationships and influences among stakeholders (socio-technical system approach Greenwell et al. 2012) with the biodiesel supply chain was weakly analysed.

Conclusions

There is an unresolved debate on the sustainability of using biodiesel to replace fossil fuel as part of a sustainable development strategy. Some countries continue fostering this industrial sector whereas others are considering reversing this type of initiatives, at least for the first generation of biodiesels.

The biodiesel supply chain is a complex system, as there is a wide range of raw materials determining the supply chain structure, concerned stakeholders, and social or environmental impacts in each country. So this “context dependency” needs comprehensive frameworks integrating all the involved dimensions, but at the same time having the possibility to be adapted to the conditions of each country.

The present chapter aims to contribute to the body of knowledge regarding sustainability analysis based on a systematic literature review, and to propose a framework to evaluate the biodiesel supply chain. This framework must then allow decision makers to dispose of more compressive tools to evaluate the sustainability of biodiesel support policies.

In order to do this, a systematic literature review methodology was applied in order to identify relevant documents of this work. Thereafter, a descriptive analysis of the results and the selected documents and their classification was accomplished. Based on these results, a new sustainability assessment framework for biodiesel, named Triple Bottom Line Extended (TBL+), was proposed. Then the application of the new assessment framework was carried out for biodiesel production.

The new proposed framework integrates the biodiesel supply chain, the sustainability dimensions, the principles, the criteria and the indicators. This implies that a hierarchical approach can provide the necessary guidance in understanding and assessing the biodiesel production system.

The biodiesel production sustainability dimensions included in the (TBL+) work were: social, economic, environmental, political and technological. With this proposal, this work aims to strengthen and expand sustainability assessments using a multidimensional view.

13 principles and 40 criteria proposed contribute to general sustainability assessment; the next step will be to define a set of indicators for each criterion. The indicators should make possible to assess a specific context of biodiesel production.

Finally, the principles, criteria and indicators (PC&I) framework methodology requires two stages: the first one is the proposal, based on the literature review, of the PC&I identification presented in this chapter. The second stage is validating the PC&I framework by means of expert consultation, which will be presented in the next chapter.

Chapter 2: Principles and criteria validation for framework sustainability assessment of biodiesel production

Introduction

Once the new hierarchical sustainability assessment framework was proposed (Chapter 1), it is necessary its validation. In this chapter, that task through expert consultation is performed. Expert consultation was selected because it has been used in the validation of conceptual models and complex issues (van der Sluijs et al. 2005; Augusiak, Van den Brink, and Grimm 2014). For this, expert survey consultations and a descriptive statistical analysis were implemented. In order to define the principles and criteria importance, 62 experts answered an online survey assessing three attributes: relevance, ease of measurement and reliability. The first result of the validation analysis was the definition of a framework composed of five dimensions (social, economic, environmental, political and technological), 13 principles and 31 criteria that would be part of a sustainability assessment of biodiesel production. The second result was the identification of potential groups and relationship between principles-criteria and criterion-criterion represented through data visualization techniques. The validated framework provides the basis to define future studies about interdimensional principles and criteria. Also, the proposed sustainability assessment framework could be adapted and applied to biodiesel production in specific contexts.

This chapter is structured as follows: In the first section, the hierarchical assessment framework is described. Then, the second section presents the validation method, which includes expert identification, online survey design and application, and the description of the statistics tools applied to survey answers (measures of central tendency, dispersion of data, principal component analysis and hierarchical ascendant classification). The third section shows the expert profile by geographic region of experts, organization type and expertise area. The fourth section presents the results of the expert consultation, the general analysis of graded dispersion, the potential correlation between importance attributes and the experts' profile, the hierarchical ascendant classification of criteria and the potential attribute correlation of criteria by sustainability dimension. Finally, section five presents the principles and criteria recommended,

the comparison of the framework proposed in this work with other similar approaches, and the potential groups and relationships between principles and criteria of different dimensions.

2.1 Hierarchical assessment framework

As described in Chapter 1, the hierarchical assessment framework was defined based on comprehensive analysis of the state of the art. About 400 documents were reviewed and 113 documents were ultimately selected (Bautista et al. 2016). The document selection was carried out through a deductive process including documents that incorporate biofuel sustainability criteria and indicators, biofuel standards and policies, and a biofuel testing framework and scorecard. Also, a condition for selection was that the documents had to consider at least the traditional dimensions of sustainable development (social, economic and environmental). The information sources employed were academic and research institutions, governmental and non-governmental institutions involved in sustainability assessment of biodiesel, scientific databases like Web of Science and Scopus, particularly the following journal databases: American Chemical Society ACS, Science Direct, Springer Journal, and Nature.com.

The proposed hierarchical sustainability assessment framework consists of three levels, as shown in Figure 1-8. The framework is composed in first level by the interaction between the five sustainability dimensions and the biodiesel supply chain stages, which helped to identify the principles for biodiesel production. The second level was made up of a set of sustainability assessment criteria linked to each principle. These criteria were identified as a measurable condition (qualitative or quantitative) aiming to assess how the sustainability principle was applied to the biodiesel supply chain. Finally, in the third level, the indicators were established to assess the characteristics or behaviors of each criterion (refer Figure 1-8 and Appendix 1).

The principles and criteria were defined in order to be applied regardless of the economic, social, political or biogeographic context, the technological conditions, or the raw materials used, among other aspects. Furthermore, to assess specific contexts, particularly conditions of the biodiesel production system or scale, a set of indicators for each criterion should be defined. Considering that the principles are the basis for defining the sustainability aspects of the biodiesel supply chain in each dimension, if the principles are validated, the dimensions linked to each principle will be validated as well. With regards to criteria, these are the measurable conditions that establish the level of application of the principles, and each criterion is evaluated by a set of indicators; if the criteria are validated, each criterion will determine the indicators

definition. Thus, the validation strategy focused on the principles and criteria that will make part of the sustainability assessment framework of biodiesel production.

2.2 Validation method of sustainability assessment principles and criteria for biodiesel production

Expert consultation was selected as the validation method of sustainability assessment principles and criteria for biodiesel production, because of its applicability in the validation of conceptual models and complex issues and the fact it is used by other authors in sustainability biofuel assessment, presented in the validation of sustainability biofuel framework (Brent and Musango 2013). As well as in the work to define the future biodiesel perspectives (Fiorese et al. 2013; Tickner 2013; Barrett 2011), and to assess the environmental degradation linked to biofuel production from stakeholder consultation (Vermeulen and Cotula 2010; Bisaro et al. 2014).

In order to validate the proposed framework, in which the five dimensions are composed by 13 principles and 40 criteria previously identified (refer Appendix 1 and Bautista, 2016), a validation strategy was implemented following six steps: (1) expert identification, (2) survey design, (3) survey application, (4) descriptive statistics analysis, (5) selection of sustainability assessment principles and criteria for biodiesel production and (6) data visualization technique. The validation process is shown in Figure 2-1, and subsequently each step is described.

2.2.1 Expert identification

- Sources of expert identification

Experts were identified through a screening of the community involved in biodiesel production and its sustainability assessment through the papers published in peer-reviewed journals, conference participation lists, and members of institution and industry such as World Energy Council, Green chemistry development institute, WIP Renewable Energies, or government institutions of Brazil, Argentina, Colombia, Chile, India, among others. Each expert was identified as having expertise with sustainability assessment of biodiesel production.

In this work four types of expert were identified according to the following definition. An industrial expert is a person who has worked in industrial biodiesel production processes for a period equal or longer than five years. A government expert is a person who has worked in

governmental institutions that develop policies, laws or politics about biofuels. In the same way, a non-governmental expert is a professional who has worked on biofuels related topics, especially in areas linked to sustainable production. Governmental and non-governmental experts are characterized by their participation as key-speaker in congress and other academic events, and as international or national consultant. A university or research expert is a professional who had published at least 5 papers in peer reviewed journal, and these papers had been cited at least 10 times.

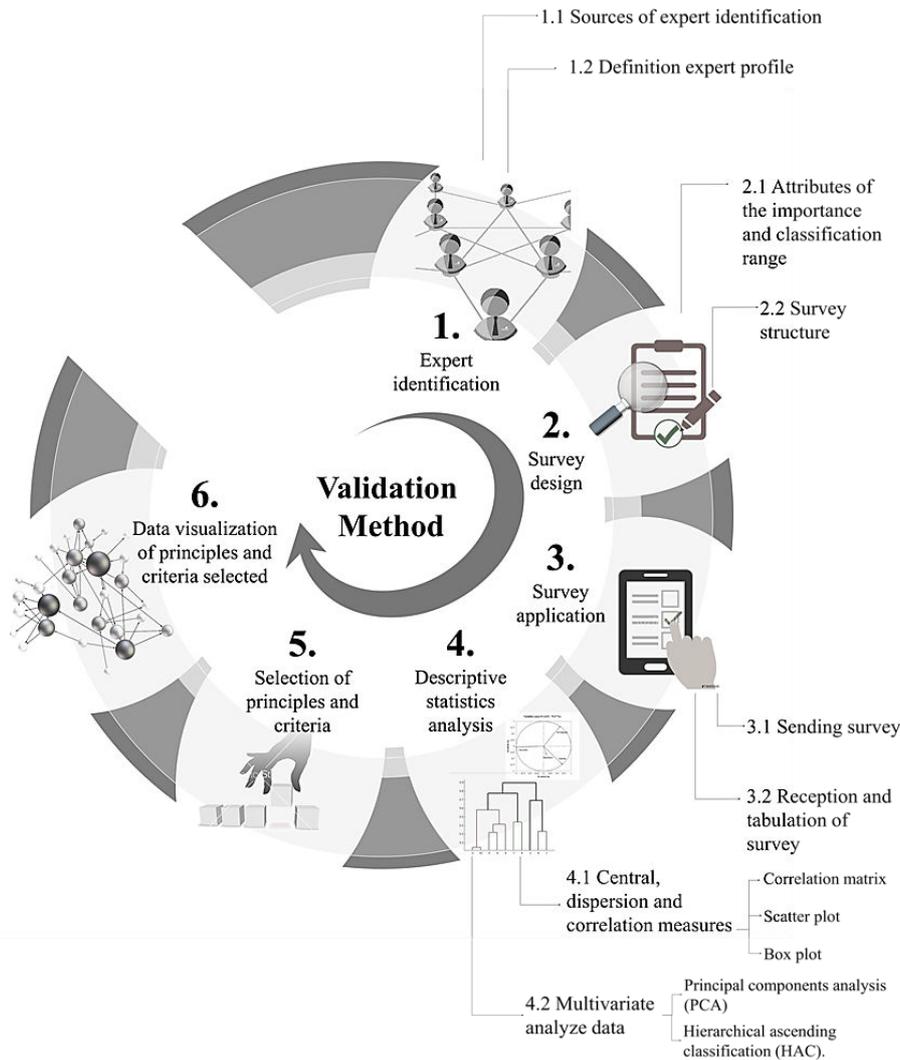


Figure 2-1. Validation Method of Sustainability Assessment Principles and Criteria for Biodiesel Production

- Definition of expert profile

This work identified key areas to be taken into account about the expert profile, initially the nationality and type of organization with which the expert was affiliated (from industry, government, non-governmental institutions, universities or research centers). After this,

expertise areas were identified for each professional (knowledge and experience), such as social, economic, political, technological and environmental associated with sustainability dimensions of biodiesel production.

2.2.2 Survey design

- Attributes of the importance and classification range

Sustainability assessment importance was defined as the impact of each principle and criterion on the assessment. The importance was the average value of three attributes: relevance, ease of measurement and reliability. The grading scale was null (0), low (1), moderate (2) and high (3); the attributes were defined as follows:

- **Relevance:** Measures the level of significance and pertinence of the criterion in the sustainability assessment of biodiesel.
- **Ease of measurement:** Measures the level of accessibility to information and the ability to perform the measurement of the criterion.
- **Reliability:** Measures how credible or certain the results of the measurement for the criterion are.

The importance was calculated using Equation 2-1. Subsequently, the principles and criteria were classified, taking into account the computed value of importance and using the grading scale shown in Table 2-1.

$$\text{Equation 2-1.} \quad \text{Importance}_i = \frac{(\sum \text{Relevance}_i + \text{Ease of measurement}_i + \text{Reliability}_i)}{3}$$

Where: “i ” is the principle or criteria.

Table 2-1. Importance grading scale of principles and criteria

Importance	Grading scale
High	2.4-3.0
Moderate	1.8-2.3
Low	0.8-1.7
Null	0-0.7

- Survey structure

The survey form was structured by multiple-choice questions about the level of importance (relevance, ease of measurement and reliability) of each principle and criteria. Then, the questions were written and translated into three languages (English, Spanish and French). The

survey was sent together with a presentation letter to the experts, in which the goals, grading scale of the principles and criteria of sustainable assessment of biodiesel production were explained in detail. Finally, a pilot survey test was applied, enabling survey improvement.

2.2.3 Survey application

Surveys were e-mailed during July 2014 to 310 experts previously identified. A month later, a survey reminder was sent. During the following two months, the survey answers were received and tabulated.

2.2.4 Descriptive statistics analysis

A statistical analysis of the results of the survey answers was conducted. Initially, techniques such as central tendency measures and variability or dispersion measures were used, and subsequent multivariate data analyses were applied (Principal Components Analysis -PCA and Hierarchical Ascendant Classification -HAC). The algorithm of descriptive statistical analysis is shown in Figure 2-2 and the tools are described below.

- Dispersion and correlation measurements

The dispersion and correlation techniques applied to the importance attributes graded (relevance, ease of measurement and reliability) were the correlation matrix, scatter plot and box plot. Initially it was applied the correlation matrix, which is a symmetric matrix where the variables are horizontally and vertically equal. In this case, the variables are the importance attributes. The matrix measures the level of corresponding correlation between each pair of attributes through the coefficient called σ . The σ is expressed by a number ranging from 0 to 1, a value of 0, indicates that no correlation is observed (Hastie, Tibshirani, and Friedman 2009).

Afterwards, a scatter plot was used because it can suggest different correlations between importance attributes with a certain confidence interval. In addition, it is possible to show linear and nonlinear relationships between attributes. The correlations may be positive (rising), negative (falling), or null (uncorrelated). A line of best fit (alternatively called 'tend-line') can be drawn in order to study the correlation between the variables. Finally, a box plot was applied, which is a graph based on quartiles, whereby a data set is displayed. It consists of a rectangle, the "box" and two arms, "whiskers" that provide information about the minimum and maximum

values, the quartiles Q1, Q2 and Q3 or medium, and the existence of outliers and symmetry of the distribution (Hastie, Tibshirani, and Friedman 2009).

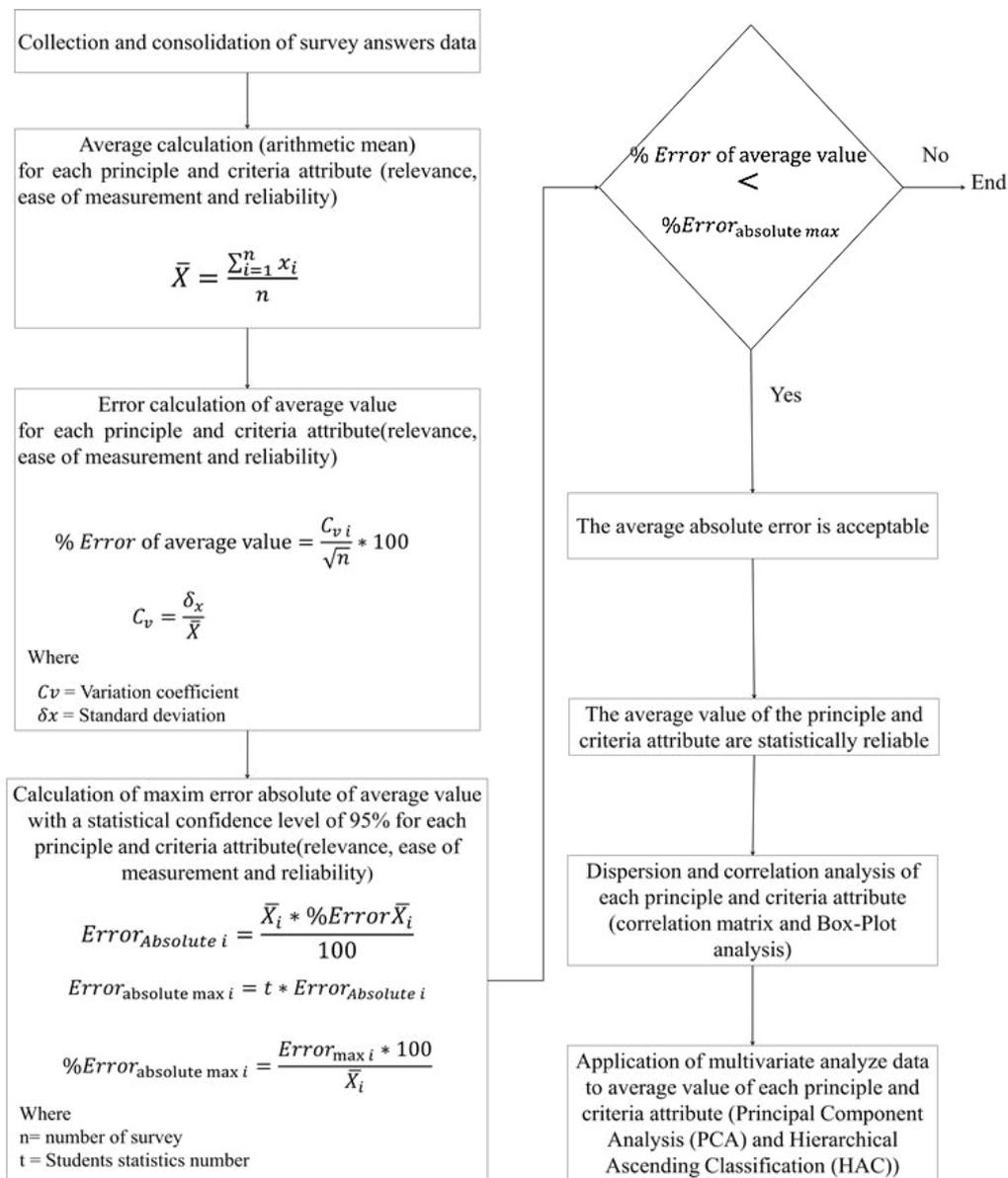


Figure 2-2. Algorithm of descriptive statistics analysis

- Multivariate data analysis

In the study of the answers given by the experts, two types of multivariate analysis data tools were used. The first tool is a Principal Components Analysis (PCA), which delivers a graphical representation of the data according to two principal axes (Syms 2008). PCA defines the principal axes regarding different variables. In this case, it studied on one hand the relevance, the ease of measurement and the reliability of the criteria considered and on the other hand, the experts' profile (nationality, area of expertise and organization type). The role of the PCA is at

first to detect pairs of variables perceived as synonyms (some variables are highly correlated), in order to reduce the dimension of the variables' space. Secondly, PCA determines which pairs of variables contribute little to the variance of the assessments. Such pairs are considered as irrelevant for a semantics description of the given group of individuals (Petiot and Yannou 2004).

The second tool is Hierarchical Ascendant Classification (HAC). It is based on general linking data using the Ward criteria aggregation method (Ward 1963). HAC regroups the individuals according to the similarity of characteristics and behavior (Fort, Lobies, and Bergeret 2011; Ward 1963). The principle is to create a partition in every stage obtained by aggregating pairwise the closest individuals (or group of individuals). The functioning of this technique is based on regrouping individuals by minimal Euclidean distance on a plan considering the same variables as for PCA. In our case, the objective is to identify several groups of criteria, which have the same global profile according to the scores of relevance, ease of measurement and reliability given by the experts.

The combination of these two analyses is relevant because it allows the researcher to visualize the correlated (or similar) variables as well as the identification of the individuals having close behaviors. This combination also makes it possible to position the groups obtained according to their evaluation with regard to the three variables chosen as the study of the criteria (relevance, ease of measurement and reliability). It can thereby identified the least good and best-estimated groups and propose a recommendation.

2.2.5 Selection of sustainability assessment principles and criteria for biodiesel production

The principles and criteria are selected if they are graded with high and moderate importance. The criteria graded with medium relevance, low reliability and low ease of measurement will be eliminated. Furthermore, if the criteria obtain high or moderate relevance, but the ease of measurement and reliability is low, then the criteria will be merged with other criteria, taking into account the hierarchical ascendant classification (HAC) that provided potential groups of criteria.

2.2.6 Data visualization of principles and criteria selected

The data visualization techniques permit better comprehension of relationships and potential correlations between the three levels of hierarchical sustainability assessment framework proposed (dimensions, principles and criteria). Afterwards, it is possible to identify central nodes in which it connects principles and criteria of different sustainability dimensions.

2.3 Results

2.3.1 Expert profile description

As a result of the expert consultation described in section 2.1, 310 experts accomplished the profile defined. Although all the experts were contacted, 62 of them answered the survey. After that, the analysis of the profile was conducted as explained in section 2.2.1.

- *Geographic region of the experts:* The 62 experts that answered the survey are from 20 different countries and their nationalities were classified by region as shown in Figure 2-3. The largest number of experts belongs to the region of Latin America and the Caribbean (68%), the second expert group belongs to the European region (21%), and a small number of experts are from the regions of Asia, North America and Africa.



Figure 2-3. Number of experts by geographic region

- *Experts by organization type:* As can be seen in Figure 2-4, most of the experts were in connection with universities and research institutes (68%), followed by the experts associated with government institutions and industries.

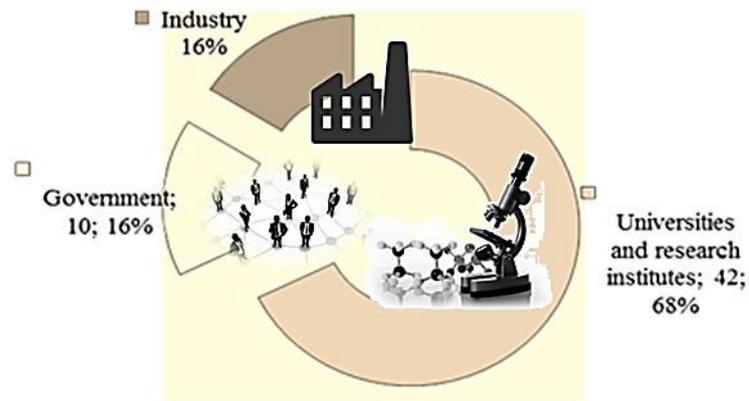


Figure 2-4. Percentage of experts by type of organization

- Experts by expertise area:* As Figure 2-5 shows, a wide variety of combinations was observed in the areas of expertise of the professionals consulted; 42% of the experts were linked with one or more expertise areas. 24% of the experts were related to the areas of environmental-technological, and 23% were only in the technological area. 11% of the specialists declared expertise in the five areas and 61% working in two or more areas, while 39% were regarded as authorities in one area. The participation of experts from multiple expertise areas was favorable for this research because it brings multiple points of view.

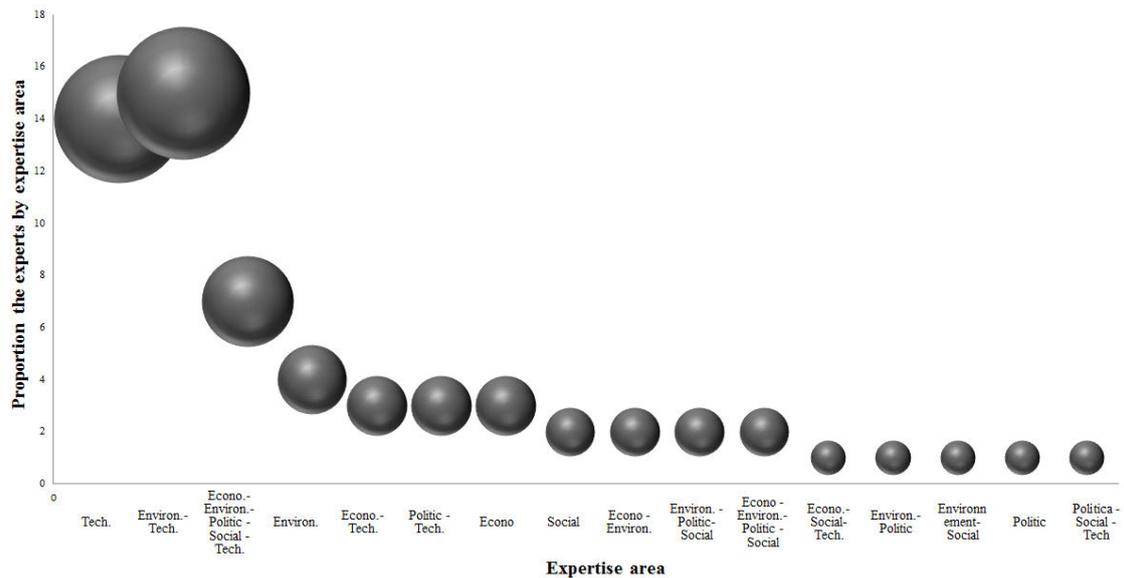


Figure 2-5. Proportion of the experts by expertise area

2.3.2 Principles statistics analysis

The average value of the three attributes graded (relevance, ease of measurement and reliability) for each principle and criterion was statistically significant based on the algorithm shown in Figure 2-2.

- Principles - General analysis dispersion

The use of average values in the subsequent statistics analysis was possible. The attribute grading of principles is shown in Table 2-2, the description of each principle is present in Appendix 1. As explained in Table 2-1 the importance given by the experts to principles was considered as high, if the average value was between 2.4 and 3.0. The principles with high variation coefficients were the same principles that obtained moderate importance grades (P5-Biodiesel promotion policy, P2-Social acceptability and P8-Economic viability). The principles associated with technological and environmental dimensions presented lower variation coefficients and graded with high importance, indicating a great deal of agreement in the grades given by experts (refer Figure 2-6).

Table 2-2. Grading averages of principles' importance

Sustainability Dimension	Principles	Importance				
		Grad	Null	Low	Mod.	High
Social	P1: Respect property and land tenure	2.7				
	P2: Social acceptability	2.4				
	P3: Promote responsible work conditions	2.7				
	P4: Prevent alteration to food supply	2.6				
Political	P5: Relationship between national and international biodiesel promotion policies	2.1				
	P6: National biodiesel production in consistency with international environmental policies	2.6				
	P7: Promote commitment to ethics and transparency	2.8				
Economic	P8: Economic viability	2.6				
Technological	P9: Technology used promotes efficiency and reduction of negative environmental impact	2.8				
Environmental	P10: Maintain or improve the air, soil and water quality	2.9				
	P11: Positive balance of greenhouse gas	2.7				
	P12: Promote the conservation and protection of biodiversity	2.8				
	P13: Energy efficiency and use of renewable energy	2.8				

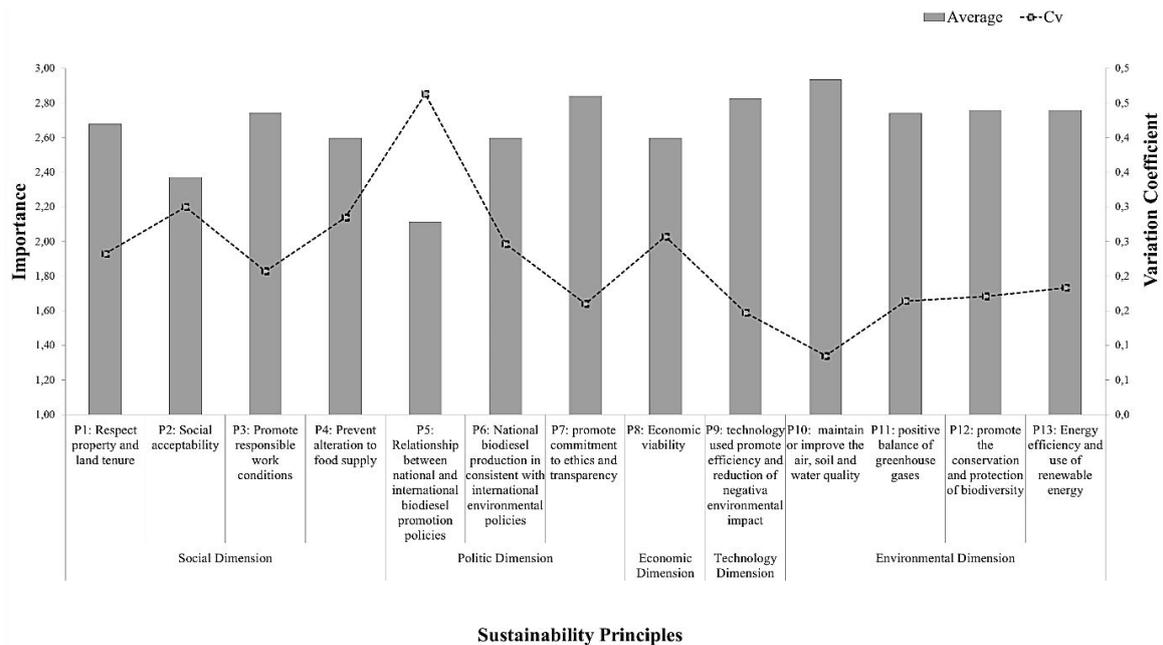


Figure 2-6. Principles importance, average and variation coefficient (Cv)

- Principles- Principal component analysis

The results of the Principal Component Analysis (PCA) set forth the potential correlation between the principles' importance and the expert profile and are shown in Figure 2-7. By combining the loading plots¹, it was possible to conclude that the principle importance grading scale does not depend on the type of organization the expert works with. Indeed, according to the PCA rules, all these variables are orthogonal, so there was no correlation between them.

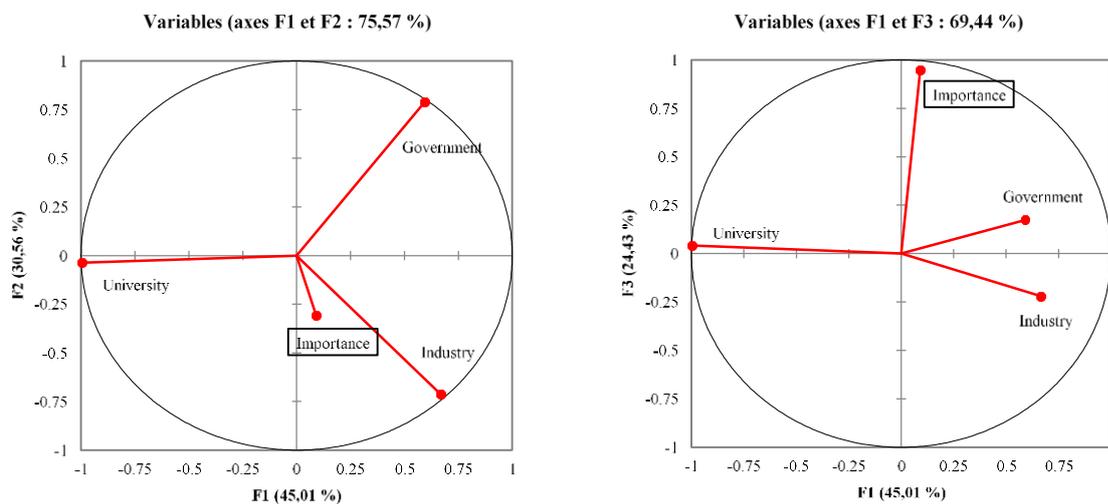


Figure 2-7. PCA loading plots concerning the type of organization

¹ The loading plot is a plot of the relationship between the original variables and the subspace dimension. It is used to interpret relationships between variables.

2.3.3 Criteria statistical analysis

The average value of the three attributes graded (relevance, ease of measurement and reliability) for each principle and criterion was statistically significant based on the algorithm shown in Figure 2-2.

- Criteria - General analysis dispersion

The average value of each attribute graded was used in the subsequent statistics analysis because each average grading obtained an absolute error less than the maximum error absolute with a statistical confidence level of 95% (refer statistical algorithm in Figure 2-2). The attribute grading of principles is shown in Table 2-3, and the description of the criteria are presented in Appendix 1.

Table 2-3. Average grading criteria for attribute

	Criteria	Relevance					Ease of measurement					Reliability					Importance				
		Grad	Null	Low	Mo	High	Grad	Null	Low	Mod	High	Grad	Null	Low	Mo	High	Grad	Null	Low	Mod	High
Social Dimension	C1-Rights of land access	2.7					1.9					1.7					2.1				
	C2-Land conflicts	2.6					1.5				1.6					1.9					
	C3-National energy security	2.5					2.0				2.0					2.2					
	C4-Environmental noise	1.9					2.0				1.8					1.9					
	C5-Changes in landscape - visual impacts	1.8					1.6				1.6					1.6					
	C6-Local prosperity	2.6					1.9				1.9					2.1					
	C7-Health & safety – employees	2.8					2.3				2.2					2.4					
	C8-Labor laws	2.9					2.2				2.2					2.4					
	C9-Food supply	2.6					1.9				1.8					2.1					
	C10-Biomass local uses	2.1					1.5				1.5					1.7					
Political Dimension	C11-Subsidy scheme	1.8					2.0				1.8				1.9						
	C12-Advanced biodiesel promotion	1.7					1.9				1.9				1.8						
	C13-Agreement biodiesel blend-diesel	1.7					2.3				2.1				2.0						
	C14-National capability in biodiesel research	2.2					1.9				1.9				2.0						
	C15-Biomass no edible for biodiesel	2.4					1.9				1.8				2.0						
	C16-National amount of land suitable	2.6					1.9				1.9				2.2						
	C17-Emission condition GHE	2.5					1.8				1.8				2.0						
	C18-Ethical commitment	2.4					1.4				1.5				1.7						
	C19-Compliance with local laws	2.3					1.3				1.4				1.7						
Economic Dimension	C20-Influence oil market/biodiesel	2.4					2.1				2.0				2.2						
	C21-Influence diesel market/biodiesel	2.5					2.3				2.1				2.3						
	C22-Production biodiesel 1a gen./biodiesel	2.2					2.4				2.3				2.3						
	C23-Influence vegetable oil market/biodiesel	2.6					2.2				2.2				2.3						
	C24- Influence glycerol market/biodiesel	2.1					2.2				2.1				2.1						
	C25-Influence advanced biodiesel Market/biodiesel	2.2					2.0				2.0				2.0						
Technologica	C26-Influence advanced biodiesel Market/veg. Oil	2.6					1.8				1.8				2.1						
	C27-Influence advanced biodiesel Techno/cost	2.4					1.9				1.9				2.1						

Criteria	Relevance					Ease of measurement					Reliability					Importance				
	Grad	Null	Low	Mo	High	Grad	Null	Low	Mod	High	Grad	Null	Low	Mo	High	Grad	Null	Low	Mod	High
C28-Influence engin trends	2.3					2.1					2.1					2.2				
C29-Influence technological learning/cost	2.3					1.8					1.8					2.0				
C30-Air quality	2.8					2.2					2.0					2.3				
C31-Efficient use of water	2.8					2.1					2.1					2.4				
C32-Local water quality	2.9					2.3					2.2					2.4				
C33-Wastes-managed responsibly	2.8					2.3					2.2					2.4				
C34-Soil quality	2.8					2.0					1.9					2.2				
C35-Greenhouse gas	2.6					1.8					1.8					2.1				
C36-Transformation-natural ecosystems	2.6					1.8					1.8					2.1				
C37-Influence fragile ecosystems	2.8					2.0					2.0					2.2				
C38-Influence wildlife	2.8					1.9					1.9					2.2				
C39-Energy used	2.4					2.0					2.0					2.1				
C40-Energy savings	2.2					2.1					2.0					2.1				

For criteria explanations, refer Appendix 1. A high average marking indicates more relevance, ease of measurement, reliability and finally importance criterion.

Overall, the criteria importance averages were between 1.6 and 2.4. The highest graded were in environmental criteria, and the lowest marked were in political criteria. Regarding the variation coefficient, the highest values are for social and political criteria, and the lowest for environmental criteria. This behavior shows that there is major disagreement in what experts graded about the importance of social and political criteria as shown in Figure 2-8.

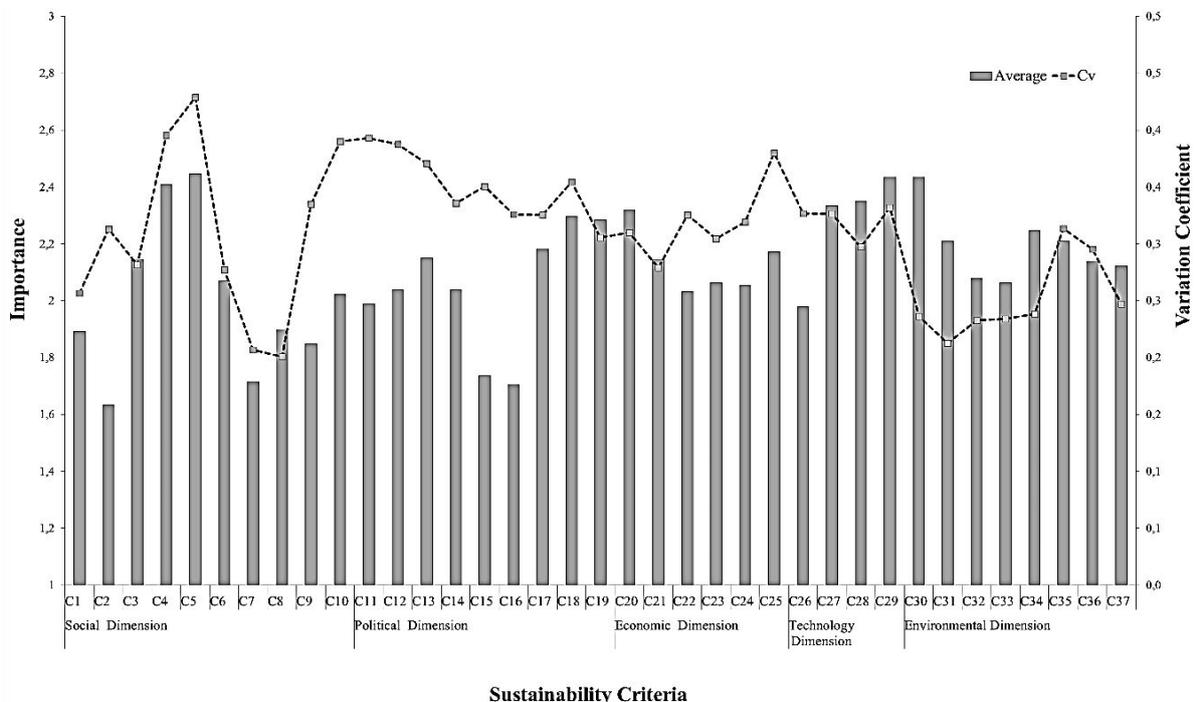


Figure 2-8. Criteria importance, average and variation coefficient (Cv).

Correlation matrix (Table 2-4) showed that there was high correlation (0.97) between the attributes ease of measurement and reliability, whereas the correlation was very low (0.23) between relevance and reliability, as well as between ease of measurement and relevance (0.15).

Table 2-4. Correlation matrix between criteria attributes

	Reliability	Ease of measurement	Relevance
Reliability	1.0		
Ease of measurement	0.97	1.0	
Relevance	0.23	0.15	1.0

Figure 2-9 shows simultaneously the scatter plot and box plot. In the scatter plot, the data distributions that shown higher asymmetry were those of the relationship between relevance-reliability and relevance-ease for measurement (Figure 2-9, A and B); thus, the correlations between relevance and these other two attributes were low. Furthermore, the data distribution that shows lowest asymmetry was in the relationship between relevance-ease of measurement (Figure 2-9, C), hence its correlation was high.

The box plot analysis is shown close to the axis in Figure 2-9. It was observed that by attribute, the relevance obtained the highest mean values compared to the other two attributes. Additionally, the box-plot analysis drew attention to the unusually low ease of measurement of criterion 19. Criterion 19 was part of the political dimension and deals with the perception level of the local community about the commitment to transparency and compliance with local laws.

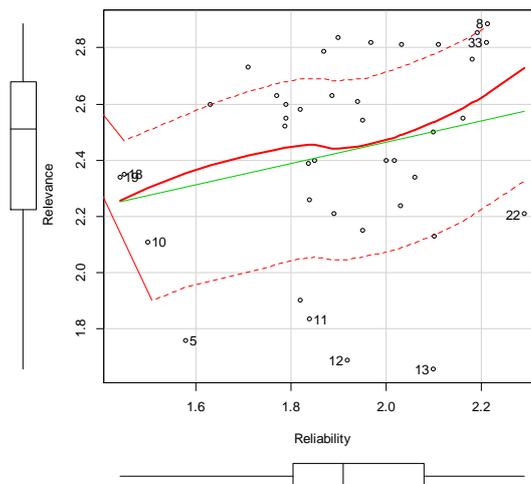


Figure 2-9. A: Scatter plot and box plot of correlation between criteria attributes (relevance and reliability)

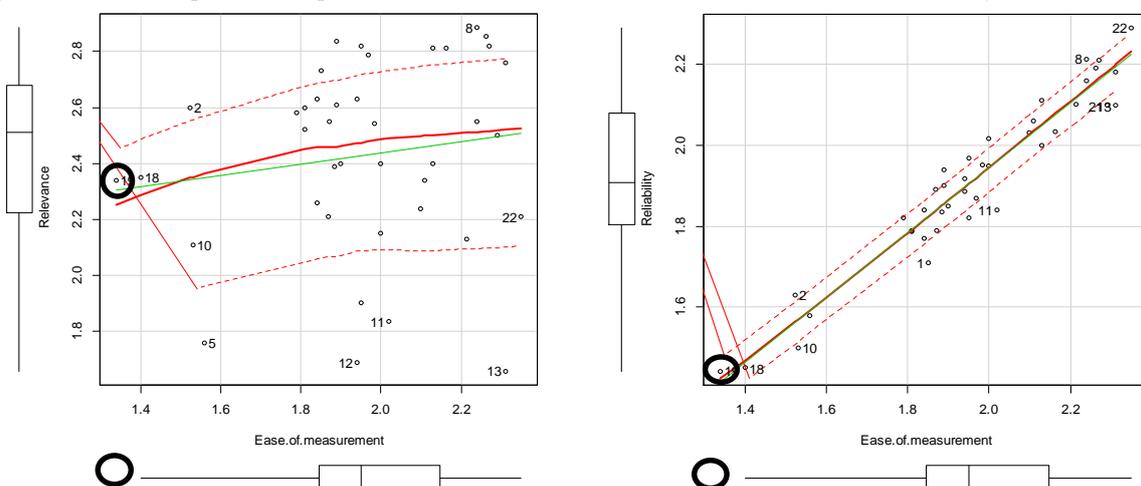


Figure 2-9. B: Scatter plot and box plot of correlation between criteria attributes (relevance and ease of measurement)

Figure 2-9. C: Scatter plot and box plot of correlation between criteria attributes (reliability and ease of measurement)

- Criteria - Principal Component Analysis (PCA)

In order to analyze the criteria another PCA was conducted. The objective of this analysis was to identify the potential correlations between the collected data. First, the expert profile was analyzed. Figure 2-10 shows the PCA loading plots of the geographical areas of the experts compared with the three attributes: relevance (R), ease of measure (EM) and reliability (Re).

In the first loading plot (Figure 2-10, A), it can be seen that geographical regions of Latin America and the Caribbean, Europe, as well as the attributes reliability-R and ease of measure-EM are well represented, since the spots indicating these variables were very close to the border of the circle. The relevance-R attribute was also well represented but not as clearly as the two other attributes. Therefore, Figure 2-10-A puts forward that the geographical regions of Latin America and the Caribbean and Europe were not correlated with the three attributes (R, EM, and Re) because they were orthogonal to each other. Another result was that the ease of measurement attribute and the reliability attribute were very close on the loading plot, which means the two attributes are correlated. In the second loading plot (Figure 2-10, B) one can see that the Asia geographical region was also orthogonal to the attributes. However, the same cannot be concluded about North America because this variable was not well represented. In conclusion, the loading plots presented highlighting the experts' geographical region did not seem to be correlated with the attributes (R, EM and Re). In this sense, the grading done by the experts does not depend on their geographical origin.

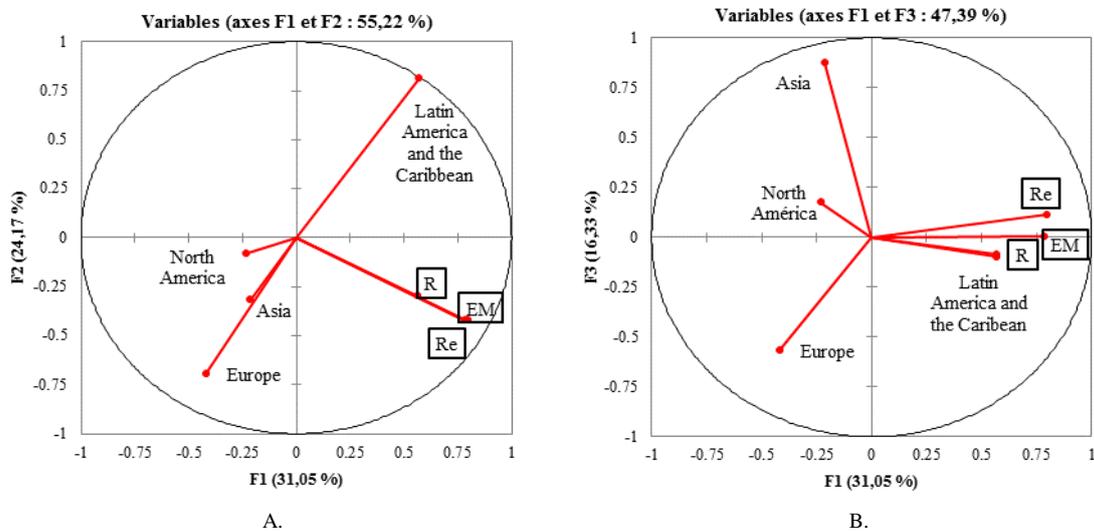


Figure 2-10. PCA loading plot concerning the geographical sector of the experts

A similar analysis was conducted in regard to the fields of expertise of the experts (Figure 2-11). The representation was adequate for the social and political proficiency of the experts, as shown in Figure 2-11, as well as for the attributes reliability and ease of measurement. Again, ease of measurement and reliability were correlated attributes. The relevance attribute and the economical, technical and environmental knowledge of the experts were moderately represented in the PCA loading plot. In a general way, the fields of expertise were not correlated with the three attributes. Indeed, all the fields of expertise are orthogonal to the attributes. This means that the field of expertise of the experts did not influence their criteria grading.

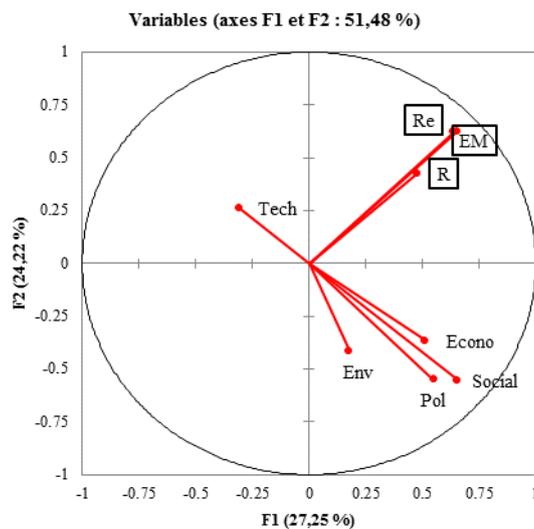


Figure 2-11. PCA loading plot concerning the experts' fields of expertise

Figure 2-12 highlights the same results regarding the type of organization. The organization type University was clearly orthogonal to the three attributes. The organization types Government and Industry were moderately well represented, but they do not seem correlated with the three attributes. Therefore, the organization type did not influence the evaluation of the experts regarding the criteria. Finally, this first PCA highlights that the criteria assessment did not depend on the experts' profile.

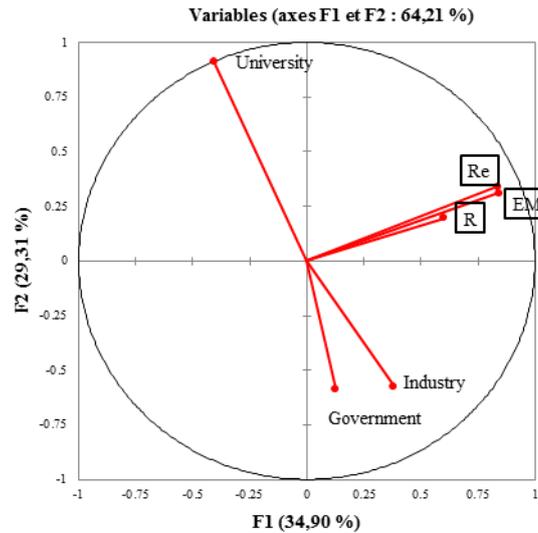


Figure 2-12. PCA loading plot concerning the type of organization

- Criteria: Hierarchical ascendant classification

Hierarchical Ascendant Classification (HAC) was carried out on all the criteria submitted to grading. The classification objective was to highlight some potential groups of criteria. The HAC dendrogram is shown in Figure 2-13. Hierarchical ascendant classification permitted the identification of seven criteria groups. The characteristics of each group are shown in Table 2-5; in general, six of seven criteria groups show high and moderate importance to be part of the sustainability assessment framework.

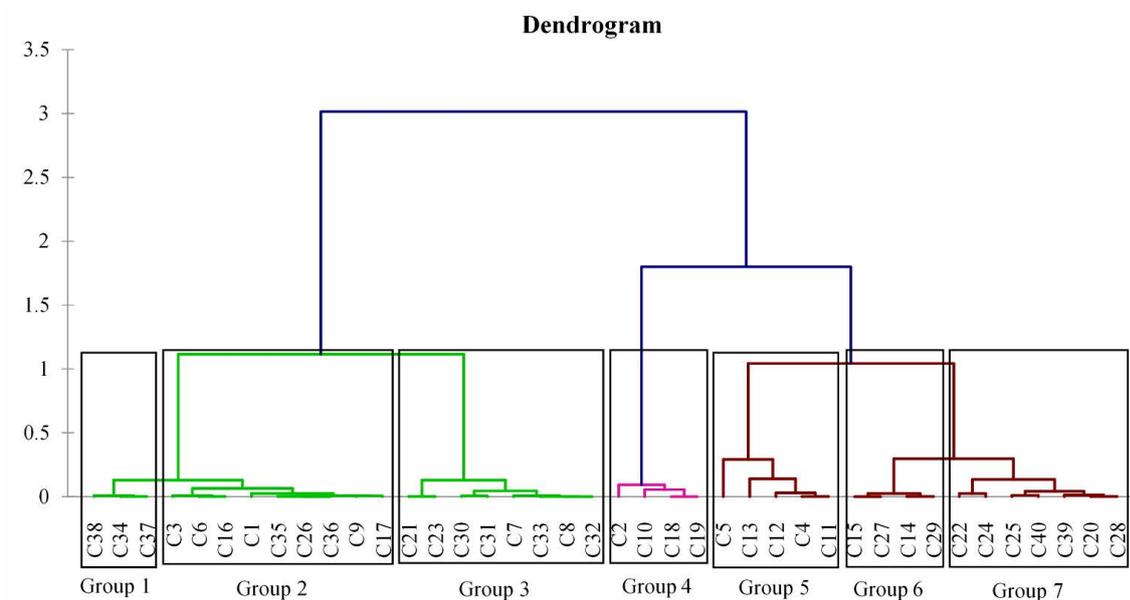


Figure 2-13. Dendrogram of the HAC concerning the criteria

Table 2-5. Characteristics of criteria groups

Dimensions	Criteria	Relevance	Ease of measurement	Reliability
------------	----------	-----------	---------------------	-------------

Social	Political	Economic	Technological	Environmental	groups	Null	Low	Mod.	High	Null	Low	Mod.	High	Null	Low	Mod.	High
					Group 1												
					Group 2												
					Group 3												
					Group 4												
					Group 5												
					Group 6												
					Group 7												

- Criteria: potential attribute correlation by sustainability dimension

In order to obtain a higher level of precision, a PCA was conducted according to each sustainability dimension. The objective of this PCA was to propose a criteria representation belonging to one dimension in relation to the three attributes (relevance, ease of measure and reliability).

The results of this analysis were reflected in a point cloud plot representing the criteria of the considered dimension according to three axes representing the attributes. For all the dimensions, the two attributes ease of measurement and reliability seem to be highly correlated. Thus, they could be thought to represent a single axis.

Concerning the social dimension (Figure 2-14), the analysis makes possible to identify the better and the worse criteria for each attribute. The most relevant criterion seems to be C1s (rights of land access), and the less relevant is C5s (undesirable visual impacts). The most reliable and easy to measure criteria were C7s, health and safety for employees, and C8s, respect of labor laws, and the less reliable was C10s, prevent alteration to biomass production for traditional local uses.

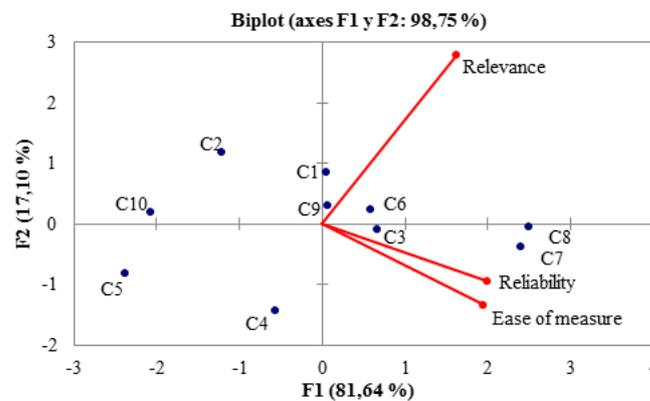


Figure 2-14. Point cloud of the social dimension

Regarding the political dimension (Figure 2-15), the most relevant criterion seems to be C16, national amount of land suitable for biomass, and the less relevant was C12, advanced biodiesel

promotion. The most reliable and easy to measure criterion was C13, agreement between national and international biodiesel blend-diesel, and the least were C18, ethical commitment and transparency, and C19, compliance with local laws. Concerning this dimension, it was important to note that the most reliable and easy to measure criterion (C13) was part of the least relevant criteria.

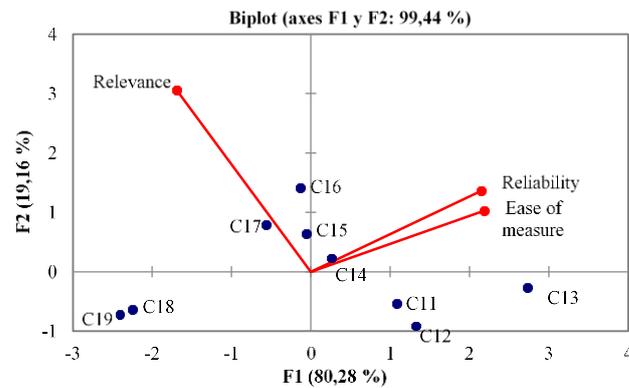


Figure 2-15. Point cloud of the political dimension

Concerning the economical dimension (Figure 2-16), the most relevant criterion was C23, influence of vegetal oil production on biodiesel production, and the least relevant was C24 influence of glycerol market on biodiesel production. The most reliable and easy to measure criterion was C22, annual production of first generation biodiesel, and the least reliable and most difficult to measure was C25, influence of advanced biodiesel market on first generation biodiesel production. In this dimension, the most reliable and easy to measure criterion (C22) was also part of the least relevant criteria.

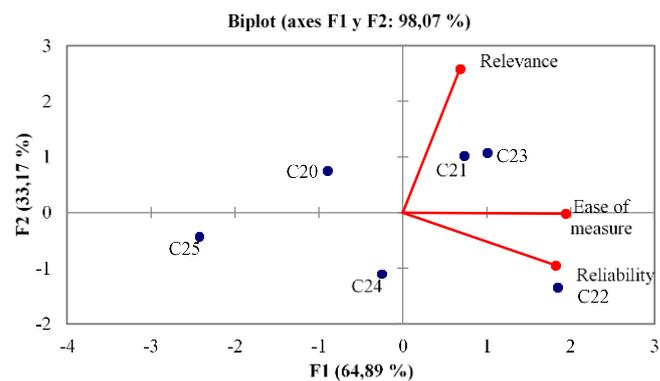


Figure 2-16. Point cloud of the economical dimension

With respect to the technological dimension (Figure 2-17), the most relevant criterion was C26, influence of advanced biodiesel production on vegetable oil market, and the least relevant was C29 development, and influence of technological learning on biodiesel production. The most reliable and easy to measure criterion was C28, influence of technology trends engines on biodiesel production, and the least reliable was C26. In this dimension, the most relevant

criterion (C26) was also the least reliable and the least easy to measure. Criterion C29 was also the least relevant criterion and was among the less reliable and less easy to measure.

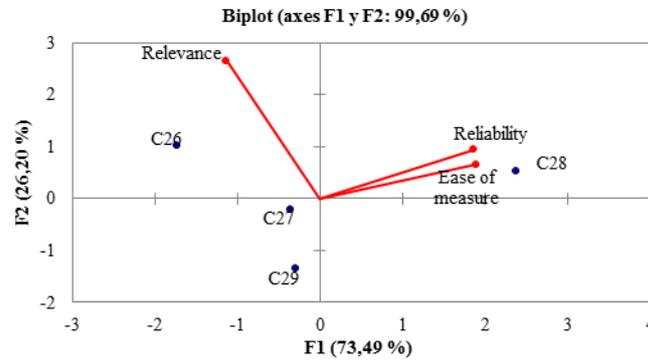


Figure 2-17. Point cloud of the technological dimension

Finally, in the environmental dimension (Figure 2-18), many criteria were moderately relevant but none was the most relevant. However, the least relevant criterion was C40 energy savings in biodiesel production. The most reliable and easy to measure criteria were C32 local water quality and C33 waste management responsibility and the most difficult to measure were C35 amount of greenhouse gas captured and C36 influence biodiesel production on transformation natural ecosystems.

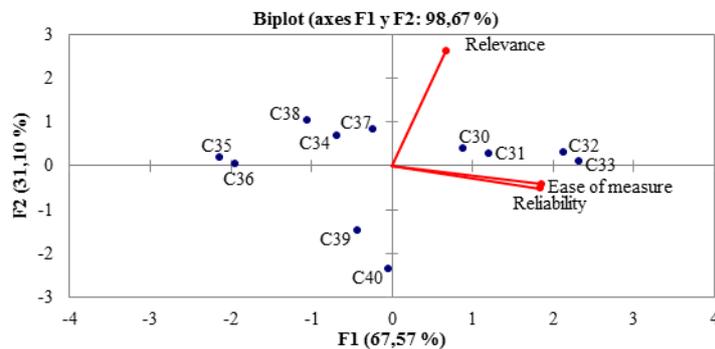


Figure 2-18. Point cloud of the environmental dimension

2.4 Selection of sustainability assessment principles and criteria

The average grading of sustainability assessment principles is shown in Table 2-2. 15% of the principles were graded as moderate importance, and 85% as high importance. Thus, all principles were recommended for the sustainability assessment framework. The higher importance grade was obtained by environmental principle P10 (maintains or improves air, soil and water quality), and the lowest importance grade was the political principle P5, relationship between national and international biodiesel promotion policies.

Regarding the result in Table 2-3, 73% of the sustainability criteria obtained high relevance and 27% moderate relevance. Therefore, the criteria graded with medium relevance, low reliability

and low ease of measure were eliminated: C4s-Environmental noise, C5s-Changes in landscape generating undesirable visual impacts and C10s-prevent alteration to biomass production for traditional local uses.

Furthermore, seven criteria obtained high or moderate relevance, but the ease of measurement and reliability were low. Then, their use in sustainability assessment framework of biodiesel production was not confirmed. The criteria in doubt were: C11p-Subsidy scheme, C12p-Advanced biodiesel promotion, C18p-Ethical commitment, C2s-Conflicts over land use, C19p-Compliance with local laws, C14p-National capability in biodiesel research. Therefore, these criteria were merged with other criteria, taking into account the hierarchical ascendant classification (HAC) that provided potential groups of criteria. In short, 13 principles and 31 criteria were recommended to become part of the sustainability assessment framework, as shown in Table 2-6.

Table 2-6. Sustainability assessment criteria recommended

Dimension	Principle	Criteria
Social	P1: Respect property and land tenure	C1s-Rights of land access
	P2: Social acceptability	C3s-National energy security
		C6s-Local prosperity
	P3: Promote responsible work conditions	C7s-Health & safety - employees
P4: Prevent alteration to food supply	C8s-Labor laws	
Political	P5: Relationship between national and international biodiesel promotion policies	C9s-Food supply
	P6: National biodiesel production consistent with international environmental policies	C13p-Agreement national/international biodiesel blend-diesel + C11p-Subsidy scheme + C12p-Advanced biodiesel promotion
		C15p-Biomass no edible for biodiesel production
P7: Promote commitment to ethics and transparency	C16p-National amount of land suitable for biomass	
Economic	P8: Economic viability	C17p-Emission condition GHE
		C20ec-Influence oil market/biodiesel
		C21ec-Influence diesel market/biodiesel
		C22ec-Production biodiesel 1a gen./biodiesel + C18p-Ethical commitment + C2s-Land conflicts
		C19p-Compliance with local laws
		C23ec-Influence vegetable oil market/biodiesel
Technological	P9: Technology used promote efficiency and reduction of negative environmental impact	C24ec-Influence glycerol market/biodiesel
		C25ec-Influence advanced biodiesel Market/biodiesel
		C26t-Influence advanced biodiesel Market/veg. Oil
		C27t-Influence advanced biodiesel Techno/cost
Environmental	P10: Maintain or improve air, soil and water quality	C28t-influence technologie trends engins /biodiesel
		C29t-Influence technological learning/cost + C14p-National capability in biodiesel research
		C30en-Air quality
		C31en-Efficient use of water
		C32en-Local water quality
		C33en-Wastes-managed responsibly
		C34en-Soil quality

Dimension	Principle	Criteria
	P11: Positive balance of GHG	C35en-Greenhouse gas
	P12: Promote the conservation and protection of biodiversity	C36en-Transformation-natural ecosystems
		C37en-Influence fragile ecosystems
		C38en-Influence wildlife
	P13: Energy efficiency and use of renewable energy	C39en-Energy used
C40en-Energy savings		

2.5 Analysis of the principles and criteria recommended

Comparing the new framework for biodiesel sustainability assessment with other similar studies (Bueren and Blom 1996; Mendoza et al. 1999; Fao and Befsci 2007; Cramer et al. 2007a; Van Cauwenbergh et al. 2007; Florin, van de Ven, and van Ittersum 2013; Kurka and Blackwood 2013), several particular characteristics can be pointed out. First, the new framework considered five dimensions for the sustainability assessment in comparison with the three traditional ones. Second, it includes the integration between the sustainability assessment dimensions and the biodiesel supply chain. Third, the relations between the levels of hierarchical structure were identified. That means the dimensions were analysed through principles, each principle was assessed by a set of criteria and each criterion by a set of indicators. Taking into account the points above, the new framework is a comprehensive sustainable assessment, while also being adaptable to different contexts and biofuel supply chains.

The biofuel sustainability assessment proposed by Buchholz et al. (2009) did not raise a hierarchical assessment framework, nor sustainability principles. Neither political nor technological criteria were defined. With regard to the validation process recommended by Buchholz et al., (2009) four attributes to evaluate the sustainability criteria were established; one of these was the importance. Regarding the last point, in this work the importance was defined as the average value of three attributes (relevance, ease of measurement and reliability) to validate principles and criteria that were part of the assessment framework proposed.

Some works about sustainability assessment tools (Buytaert et al. 2011; Silva Lora et al. 2011; FAO and BEFSCI 2012; Cucek and Kravanja 2012) described the performance and applicability of an existing tool selection that are potentially useful for sustainability assessment of bioenergy systems. Unlike this work, the hierarchical framework, the principles and criteria assessment were defined. In addition, this work proposed a framework that linked the stages of the biodiesel supply chain with the sustainability assessment.

The research of Kurka & Blackwood (2013) did not raise a hierarchical assessment framework, nor sustainability principles. This work considered, in addition to three traditional sustainability

dimensions, the technical dimension. The focus of this document was to identify sustainability criteria and indicators and their validation linked to a case study. Finally, Florin et al. (2013) proposed sustainability principles and criteria to small farmers of biomass biodiesel production; it was emphasized to indicate definition, and did not take into account the technological dimension.

In the assessment framework definition of this work, the existence of a horizontal consistency was considered. This means that principles or criteria appearing at the same level do not have any overlap. Regarding the horizontal relationship between criteria, the Hierarchical Ascendant Classification (HAC), seven potential groups of 40 criteria were identified (Figure 2-13); in each group there were criteria linked to different sustainability dimensions. After applying the validation strategy, 13 principles and 31 criteria were proposed (Table 2-6).

2.6 Data visualization technique of principles and criteria

With the aim to visualize the relationships between the five sustainable assessment dimensions, the 13 sustainable principles and the 31 assessment criteria, a display of data in visualization technique (graph drawing²) was applied (Figure 2-19). The graph drawing is a data visualization technique that allows better representation of heterogeneous information, multi-dimensional data, importance and correlation between data.

In the graph drawing, nodes represent principles and criteria, and edges represent relations between nodes. The node size represented the importance average grading. A force-directed algorithm was applied that combines a multilevel approach which overcomes local minimums, with techniques such as approximates-short and long-range force (Hu 2005). In the network, the nodes with more connections were located in central areas, and these central nodes tend to have bigger influence on the other nodes. Furthermore, greater proximity between nodes was indicative of similar or equal importance between nodes and, in turn, of node groups on the network.

Three central nodes (CN) were identified whose visualization is shown in Figure 2-19. The first central node (CN1) includes the political, social and technological principles and criteria, and

² Graph drawing is an area of mathematics and computer science combining methods from geometric graph theory. The basic graph drawing is given a set of nodes with a set of edges (relations); calculate the position of the nodes and the curve to be drawn for each edge. It requires the definition of properties and classification of layout according to the types of graphs to which they can be applied (Herman et al. 2000).

only two environmental ones. In general, in this central node the importance grading was between moderate and high. In addition, it was observed that the most central nodes were the political criterion C17 about policy conditions by greenhouse gas emissions in the life cycle of biodiesel production, and technological criterion C26 regarding the influence of the advanced biodiesel market on the vegetable oil market. Furthermore, greater proximity between social and environmental criteria nodes was identified, because such criteria obtained equal importance grading.

The second central node (CN2) is related, mainly, to environmental principles and criteria. However, two social criteria and two economic criteria are included. Overall, the highest importance grading was given to the principles and criteria of this central node. It was identified that the principle P10 about maintaining and improving air, soil and water quality, was the most central node in this group, because it was graded with the highest importance, like their related criteria.

Finally, the third central node (CN3) shows the highest heterogeneity, probably because it includes economic, environmental, technological and social criteria, whose importance grading was moderate. In addition, greater proximity between nodes is shown, indicating similar importance.

In short, the three central nodes are conformed by interdimensional principles and criteria. For example, in all groups the environmental criteria are present, and particularly, environmental criteria are related to social and economic criteria. The forces-directed and approximate force between criteria shown in Figure 2-19 calls attention to the possibility of evaluating two or more sustainability dimensions through one criterion.

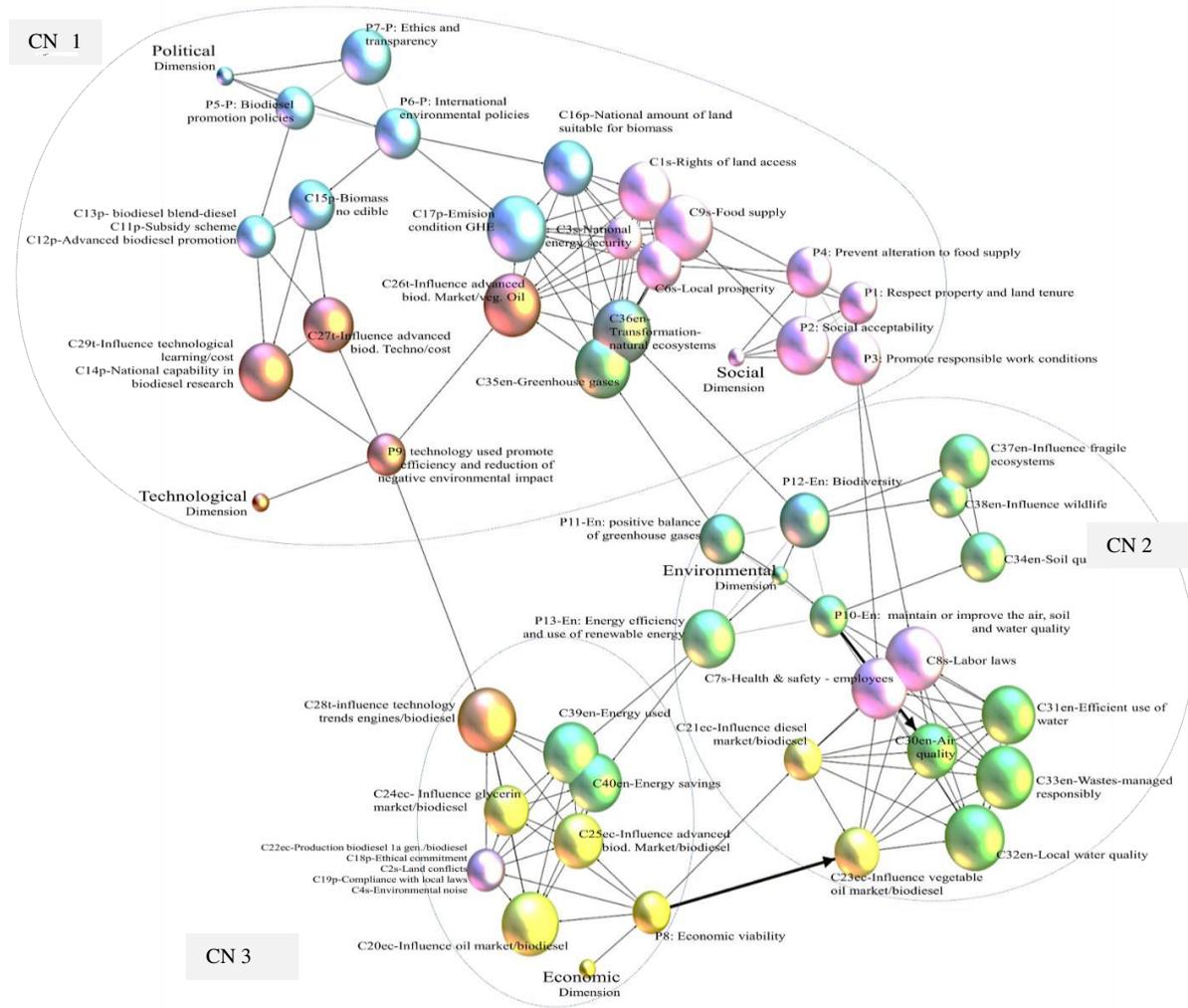


Figure 2-19. Principles and criteria framework visualization

Conclusions

The present chapter showed the validation of principles and criteria through expert consultation, a new validation methodological approach which integrates the technological and political dimensions to the three traditional dimensions of the TBL for sustainability assessment (social, economic and environmental) in biodiesel production. Likewise, it was possible to establish the principles and criteria that permit the assessment of the sustainability of biodiesel production. Finally, the relevance, reliability and ease of measurement of principles and criteria were defined. This new methodological approach permits the integration of expert consultation, descriptive statistics analysis and data visualization.

As a result, five dimensions, 13 principles and 31 criteria were validated and recommended to become part of the sustainability assessment framework for biodiesel production. Furthermore,

three central nodes were identified, comprised by interdimensional principles and criteria that permit the visualization of relationships between dimensions, principles and criteria.

The hierarchical sustainability assessment framework of PC&I for biodiesel production proposed has the following limits: First, the framework applicability is to renewable energy whose raw material is biomass. Second, it is necessary to define a set of indicators for each criterion, for assessment of a specific context of biodiesel production. Third, most of the experts belong to the geographical area of Latin America, the type of organization Universities and the area of expertise Technological and Environmental, thus it is important to strengthen expert consultation with experts in other geographical areas, organizations and expertise areas. However, it is important to note that, according to the results of the Principal Component Analysis followed in this work, the grades given by the experts to principles and criteria were not correlated with their geographical origin, type of organization or expertise area.

Regarding the attributes of importance that were proposed (relevance, ease of measurement and reliability) to grade the impact of each principle and criterion on the assessment framework, a high correlation was identified between ease of measurement and reliability. For example, if it is easing the measurement of a criterion, it is possible to repeat the measurement, verify the measurement and increase reliability in regard to the criterion. Therefore, the attribute Ease of Measurement can be eliminated and the importance grading can be performed through the attributes Relevance and Reliability.

In the next chapter, a System Dynamics (SD) model will be designed and implemented in Stella[®] software, in order to show the interactions between dimension through the principles, criteria and indicators validated in this chapter.

Chapter 3: Definition and design of a system dynamic model for sustainability assessment of biodiesel production in Colombian context

Introduction

This research has followed a stepwise design for a new hierarchical sustainability assessment framework of PC&I (principles, criteria and indicators) for biodiesel production. The first stage was to define such framework (Chapter 1). In the second stage, the PC&I were validated through several mechanisms that included expert consultation (Chapter 2). In this chapter, a system dynamics based model is designed as methodological tool oriented to display the characteristics, interaction, and influences among the PC&I that compose the sustainability assessment framework.

The system dynamics model was developed and applied to a particular case, assessing the sustainability of biodiesel production in Colombia, following five stages: problem definition, dynamic hypothesis formulation, description of the model boundary, description of the model structure and the definition of the functions that will describe the selected indicators, and testing of the model and result analysis. Following, each one of these stages is described.

3.1 Background of Colombian biodiesel production

Industrial production of biodiesel in Colombia started in 2009. Currently, it is produced in seven process plants, most of them located close to oil palm cultures. The total installed capacity of the country is 581,000 t / year. Production of biodiesel in 2014 was 518,042 t. In 2013, 503,337 t were produced from 458,772 t of palm oil that corresponds to 44% of the Colombian production of that oil (Fedebiocombustibles 2015). African oil palm is growth in 546,696 ha, 82,3% in production and 17,7% under development (Fedebiocombustibles 2015). Compared to 2009, biodiesel production has growth 150%. Despite the technology implemented (Desmet – Ballestra, CMB Bernardini, etc.), all the biodiesel is produced by transesterification using alkaline homogeneous catalyst and implementing the wet process for biodiesel purification. Further information about current biodiesel production technologies can be referred in

bibliography references (Knothe, Gerpen, and Krahl 2005; Torres et al. 2008; Sivasamy et al. 2009; Oh et al. 2012; Santori et al. 2012; Abbaszaadeh et al. 2012).

While the law that promotes biofuels production and commercialization for diesel engines was promulgated in 2004, only in 2008 a policy to produce biofuels in a sustainable way was established (CONPES and DNP 2008). The law establishes tax exception for some cultures, including oil palm, and for the blend biodiesel – diesel. Some of the objectives of that policy are to increase the competitiveness of biofuels production, to generate employment, rural development and society welfare, to promote Colombian biofuel exports, to diversify the sources of energy and to guarantee the environmental sustainability of biofuels implementing sustainability indicators to make decisions related to its supply chain (CONPES and DNP 2008). Since 2013, it is possible to establish mandatory blends of biodiesel and diesel higher than B-10, depending on the developments in engine technologies and on the national production of biodiesel (Minminas 2011). Diesel and biodiesel prices are established monthly by the Ministry of Mines and Energy, considering the international price of crude oil, production costs and taxes, among several factors.

3.2 System dynamics application in biofuels analysis

System theory is the transdisciplinary study of phenomena. It investigates the principles common to all complex entities, and the (usually mathematical) models which can be used to describe them. A system can be said to consist of four things. The first is objects – the parts, elements, or variables within the system. These may be physical or abstract or both, depending on the nature of the system. Second, a system consists of attributes – the qualities or properties of the system and its objects. Third, a system has internal relationships among its objects. Fourth, systems exist in an environment. A system, then, is a set of things that affect one another within an environment and form a larger pattern that is different from any of the parts (UT 2010; Le Moigne 2006).

In the context of this work, biodiesel production is considered a complex system due that its analysis is conducted through multilevel variables called principles, criteria and indicator – PC&I. Their properties are linked to assessment dimension of sustainability (economic, social, environmental, politic and technological). Furthermore, biodiesel production has relationships among an environment related to supply chain in geographical contexts.

The formalization of a model for biodiesel production system can be done from the modeling of system dynamics (Bantz and Deaton 2006; Szarka et al. 2008; Pruyt and Sitter 2008; Franco and Flórez 2009; Oviedo et al. 2011; Franco, Zapata, and Dyner 2015; Josephine K. Musango et al. 2012), simulation based on agents (Halog and Manik 2011), with the use of techniques such as multi criteria evaluation, fuzzy logic, structural analysis / method of scenarios and technological evaluation (Edgard Gnansounou 2011; Beall, Cadoni, and Rossi 2012; Rose 2014).

System dynamics (SD) is a methodology that combines analysis and synthesis to establish and to formalize relationships between different information flows and structures of a complex system, which facilitates the distinction of feedback mechanisms (Forrester 2013). Thereby, through system dynamics modeling it is possible to understand how the organizational structure, policies and delays in decision-making interact and influence the success or failure of a company or system (Forrester 2013).

Between the different applications of this methodology, SD has been recently used by several studies that analyze the market of renewable energy sources. Bantz & Deaton (2006) modeled the biodiesel market to understand the reasons why biodiesel production capacity growth exponentially in the United States. Wit et al. (2010) applied and developed the “Biotrans” model in Europe, to optimize costs along the supply chain of biofuels. Oviedo et al. (2010) explained the production and consumption of alternative fuels, like biofuels, based on country’s policies, environmental protection and agricultural development. A SD model representing the behavior of the biodiesel industry worldwide, considering conflicting points of view about the use of biofuels was proposed by Oviedo et al. (2011) for assessing biodiesel sustainability using a reduced number of indicators and focused in market behavior. Musango et al. (2011) and Musango et al. (2012) implemented SD using the Bioenergy Technology Sustainability Assessment (BIOTSA) model to assess the effects of biodiesel development on selected sustainability indicators for the Eastern Cape Province of South Africa. Barisa et al. (2015) proposed a SD model for finding the most effective biodiesel policy strategies in Latvia. Franco et al. (2015) performed a SD modeling to approach the understanding of biofuel market in Colombia.

Although these studies provide a valuable contribution to sustainability analysis in the biofuels sector, they do not consider the entire sustainability dimensions proposed in this work: economic, social, political, environmental and technological. Moreover, these studies do not

explain the data collection process and how the selection of mathematical relationships between different variables was done.

3.3 Systems dynamics methodology

SD methodology has five general steps: problem definition, dynamic hypothesis formulation, description of the model boundary, description of the model structure and definition of the functions that will describe the selected indicators, and testing of the model and results analysis (Bérard 2010; Josephine Kaviti Musango 2012; Lee et al. 2012b). The methodology steps are shown in Figure 3-1.

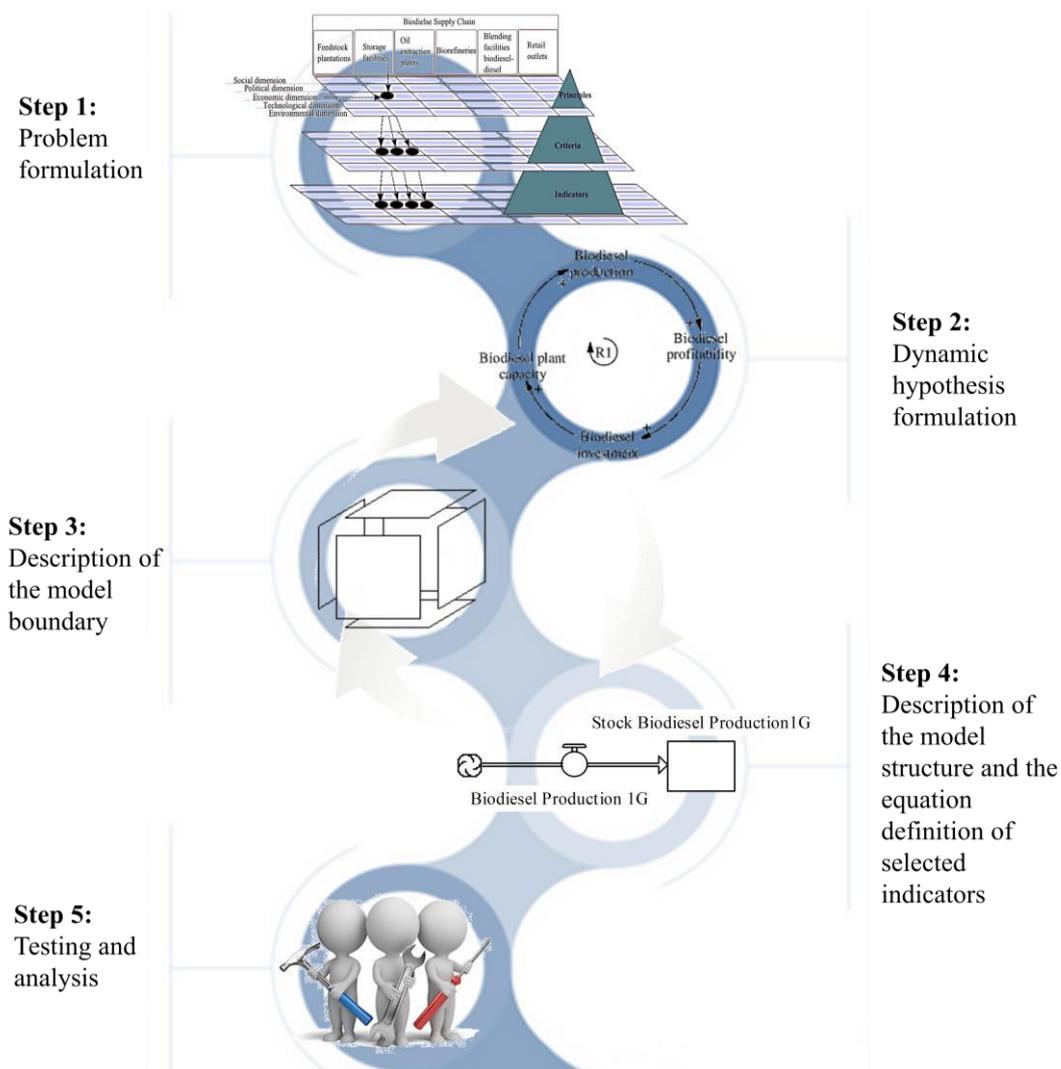


Figure 3-1 System Dynamics methodology, based on (Lee et al. 2012b) and (Bérard 2010)

3.3.1. Problem formulation

Problem formulation is the identification of the purpose of the model and the focus problem. To identify these two aspects of the system under study is fundamental to guide the modeler to

define the boundary of the model, the research hypothesis and the time horizon (Sterman 2002; Josephine Kaviti Musango 2012).

3.3.2. Dynamic hypothesis formulation

This step involves developing a working theory to explain the problem that is being considered, which is usually called dynamic hypothesis, because it describes the dynamics of the behavior of a system based on the underlying feedbacks and interactions between the different parts. The dynamic hypothesis helps to develop an appreciation of the complexity of the system. This is essentially accomplished using systems thinking approach as suggested by Ti-yan et al. (2008); Lee et al. (2012) and Brent & Musango (2013). To formulate the dynamic hypothesis, causal loop diagrams to explain the relationships between the variables of the models have to be developed.

A causal loop diagram comprises connections of variables by causal links, which are denoted by an arrow. The links usually have either a negative or positive polarity denoted by “+” and “-” respectively. The negative polarity implies that, if the cause decreases (increases), the effect increases (decreases). On the other hand, a positive polarity implies that, if the cause increases (decreases) the effect increases (decreases). If a feedback loop has an even number of “-” signs, it is a positive loop. If it has uneven number of “-” signs, it is a negative loop. A positive feedback loop is also known as a reinforcing loop and it is normally marked with “R”. It is known as a reinforcing loop because it is an amplifying or enhancing feedback loop. On the other hand, a negative feedback loop is also known as a balancing loop and it is normally marked with “B”. It is a balancing loop because it is a stabilizing, goal seeking and regulating feedback loop (Sterman 2003; Josephine K. Musango and Brent 2011), a general diagram notation in shown in Figure 3-2.

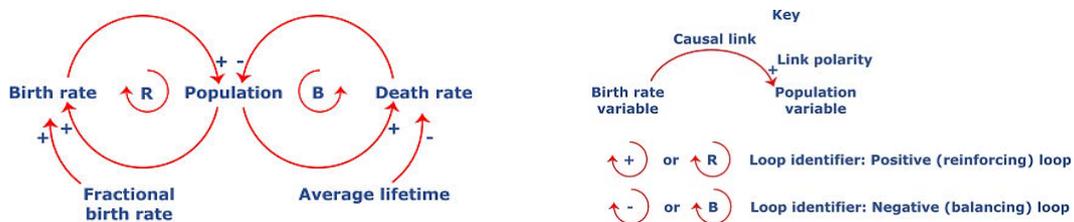


Figure 3-2. General diagram notation (Sussman 2012).

This polarity labelling is an important step of qualitative modelling in system dynamics and it is an initial step towards developing the feedback structure described by stock and flow diagrams and finally by equations.

3.3.3. Description of the model boundary

The purpose of the model boundary definition is to identify the endogenous and exogenous indicators that permit the best explanation of the problem (Sterman 2003). Endogenous indicators are calculated using the model, while exogenous indicators are fed to the model. The importance of the indicator (relevance, reliability and ease of measurement) is a selection criteria for including it in the model (refer chapter 2). Then, indicators that most influence the system will be included in the model. To decide if an indicator is endogenous or exogenous it is necessary a clear definition of the problem (Josephine Kaviti Musango 2012).

3.3.4. Description of the model structure and the equation definition

Each indicator incorporated in a causals loop diagram should be represented in the dynamic model using functions (equations or graphic functions) or parameters. The definition of dynamic indicators of the model starts establishing if they have a pre-established and demonstrated relation. If the relation between the variables is not pre-established, the equation will be obtained from historical data by using least squares algorithms (Draper, Smith, and Draper 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 performed as follows:

- Calculate 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 ; $\sqrt{1}$, $\sqrt{2}$]).

$$\text{If } \begin{array}{l} \text{“}F - \text{test Analysis of Variance “} > \text{“}F \text{ table } (\alpha; \sqrt{1}, \sqrt{2})\text{”} \\ \alpha = 0,10 \end{array}$$

the equation is significant, so it can be used to represent the relationship between the variables. In addition, each variable must be significant (α) in the equation considering the same approach.

- The equation used in the dynamic model accomplishes the above criteria and has the highest values of R^2 and R^2 adjusted. The value of R^2 adjusted measures how the equation and the data fit. However, to measure the predictive ability of the designed model it is necessary to use the criterion of error indicators.

- A Cross-Validation of Regression Models would be conducted if all data are used in equation definition (Comparison of Sparse and Jack-knife partial least squares regression methods) (Karaman et al. 2013; Kleijnen 1995; Picard and Cook 2012; Steyerberg et al. 2001)

Once the equations have been selected, they can be implemented to the SD model construction using a suitable tool, for example Stella® or VENSIM®, for further simulation and validation. It is important to note that the modeler will know how reasonable the conceptualized diagram is, only after the model of the system has been finished and the simulation has been performed 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 of them define their state (stock) and which define changes in their state (flows). The variables not included in these two classifications are auxiliary variables (Michael J. and Robert A. 1997). The following guideline may be useful to help to identify stocks and flows:

- Stocks usually represent nouns and flows usually represent verbs
- Stocks do not disappear if time is stopped (if a snapshot were taken of the system). Contrary, flows disappear in the same situation
- Stocks send out signals (information about the state of the system) to the rest of the system.

3.3.5. 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 element of the model 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 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 and exceptional situations 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 obtained using the model as well as the behavior of different structures in order to perform a sensitivity analysis by modifying values of several variables.

3.4 Application of SD methodology in the biodiesel sustainability assessment

3.4.1 Problem formulation

The problem formulation was conducted using the sustainability assessment framework of biodiesel production proposed in chapter 1 (refer Figure 1-8), which identifies dimensions, principles, criteria and indicators -PC&I for developing a sustainable biodiesel production. The focus of the problem is to define the causal loops between PC&I in order to promote sustainable biodiesel production in the Colombian context.

A further aspect of the problem formulation is the time horizon of the model. Very important works developed by institutions as the International Energy Agency (IEA), the Energy Information Agency (EIA) of the United States and Unidad de Planeación Minero Energética of Colombia, project energy production, consumption and demand according to the source considering 2030, 2035 or 2050 scenarios (BP 2011; EIA 2011; IEA 2011a; Gonzalez et al. 2014; UPME and MME 2015). In the same way, sustainability assessment requires to predict the behavior of the system for long periods, usually between 30 and 50 years (ICTSD 2008; Bringezu, Brien, and Howarth 2009; Josephine K. Musango et al. 2011; Gerbens-Leenes et al. 2012; Kampman, Grinsven, and Croezen 2012). For this reason, this study considers the period 2013 – 2030 as the time horizon.

3.4.2 Dynamic hypothesis formulation in the biodiesel sustainability assessment – Causal loop cycles

The research hypothesis of this dynamic model is that the sustainability assessment framework is suitable for assessing the sustainability of the biodiesel production, and SD is an appropriate methodological approach. The assessment framework model would provide insights about the effect of biodiesel production in Colombia on the selected sustainability indicators, enabling the analysis of the outcomes through predicted scenarios.

The description of the dynamic behavior based on the underlying feedbacks and interactions between selected indicators is shown through five causal loop diagrams linked to each sustainable dimension. The aim of the causal loops is to provide an endogenous explanation of biodiesel production in Colombia. The interaction and relationships was identified through three strategies, first literature reviews, second historical data related selected indicator, and third current condition in Colombian context.

Economic dimension

An overview of the economic dimension of biodiesel production in Colombia is presented in Figure 3-2. It consists of two reinforcing loops (R1 and R2) and two balancing loops (B1 and B2). From Figure 3-2, balancing loop B1 shows that increments in palm oil price increase biodiesel production costs, decreasing biodiesel profitability. A decrease in biodiesel profitability reduces biodiesel production, decreasing its sales. Finally, if biodiesel sales diminish, palm oil price diminishes too.

In the reinforcing causal loop R1 the scenario when glycerol is valorized through 1,3-Propanediol production (PDO) in Colombia is considered. This is a new technology, still under development, and currently it is not implemented in Colombia but it is project to build a bio-propanediol (1.3 PDO) production plant in Malaysia in 2017 (Bioplastics News 2014). This country is one of the world largest producers of palm oil. The global 1,3-Propanediol market is estimated to reach USD \$621.2 million by 2021, with increment of 10.4% between 2014 and 2021(MM 2015). PDO is a feedstock employed for manufacture of many chemicals and materials, and it has the potential to replace ethylene glycol in PET production (Posada et al. 2013). The reinforcing loop R1 shows that if glycerol is valorized through PDO production,

direct contract employees, number of accidents, occupational diseases, and child labour in palm cultivation (for further description refer Appendix 3). The causal relation between the quality of employment and lands for palm cultivation is represented in the balancing loop B3. The increment in the quality of employment increases the amount of land for oil palm cultivation. The contrary behavior is observed for the effect of land for palm cultivation and the quality of employment. If land for palm cultivation increases the quality of employment will reduce.

Relationships have been observed between indirect and direct land use changes, social indicators and palm oil production. In the palm regions in Colombia, the increment of palm oil production promotes an increase of lands for palm cultivation. According to different studies, new lands for palm cultivation come, in descending order of area, from agricultural, livestock and forest and ecosystem lands (BID and MME 2012b; Romero et al. 2012; Castanheira, Acevedo, and Freire 2014). The new lands for livestock come, mainly, from forest and ecosystem lands and, to a lesser extent, from agricultural lands. In this way, the increment of lands for palm cultivation has an indirect effect on the reduction of forest and ecosystem lands.

Regarding livestock lands, there are social and economic indicators that influence their increment. An improvement in local economies promotes a reduction in poor population that, in consequence, increases the consumption of the basic grocery products, including meat. That has a positive influence on the livestock lands (DANE, 2013). Besides, in the local economies the increment in palm cultivation and palm oil production, promotes the reduction of poor population.

The relationships mentioned before are represented in the balancing loop B4, which shows that increments in palm oil production reduce poor population. In turn, a reduction in poor population increases livestock lands which consequently decrease forest and ecosystem lands. Furthermore, if forest lands decrease and soil loss in palm cultivation increases, the crop yield in palm cultivation will diminish which consequently will reduce the palm oil production.

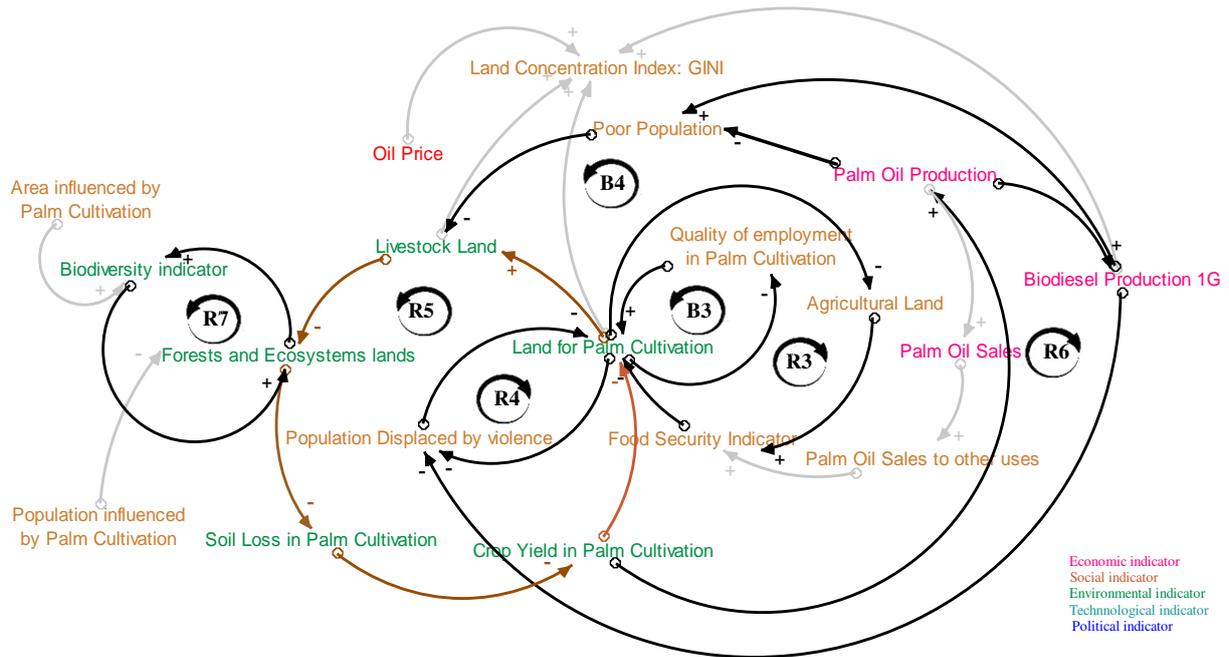


Figure 3-3 Causal loop diagrams of the social dimension

Reinforcing loop R3 in Figure 3-3 shows that the food security indicator, defined as the ratio between agriculture lands and lands for palm cultivation (indicator proposed by FAO (2014)), is directly proportional to both variables. According to the reinforcing loop R4, an increase in lands used for palm cultivation decreases the population displaced by violence and vice versa.

Historical data in Colombia related to biodiesel production (Fedebiocombustibles, 2015) and poor population (DANE, 2013) in the regions influenced by lands for palm cultivation show that biodiesel production is increasing and poor population too (refer to reinforcing loop R6 and Figure 3-4). At the same time livestock lands increase. The description of the reinforcing loop R5 is shown in the environmental dimension causal loop.

According to reinforcing loop R7, the forest and ecosystem lands as well as the biodiversity indicator are affected by the social indicator area influenced by palm cultivation and population influenced by palm cultivation. The biodiversity indicator in the context of this research is the relation between the forest and ecosystem lands, the area influenced by palm cultivation and the number of species of flora and fauna. An increment in biodiversity indicator equally increases the forest and ecosystem lands, which is also swayed by population influenced by palm cultivation. In parallel, the land concentration Index-GINI analysis permits to identify that increments in oil price, livestock lands, lands for palm cultivation and biodiesel production augment its value.

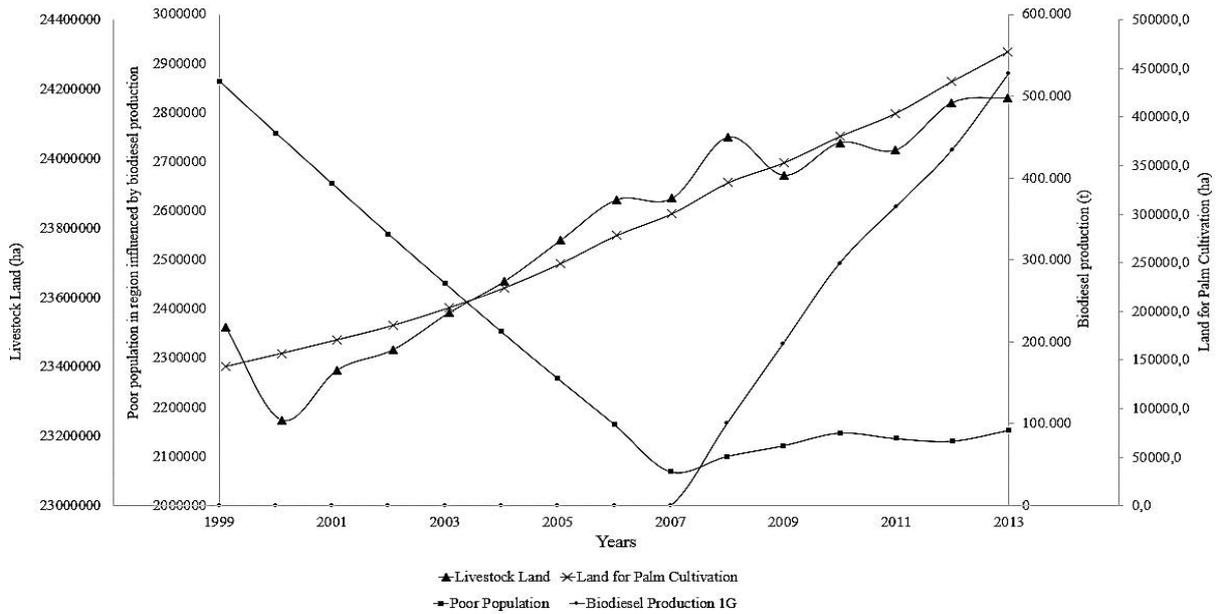


Figure 3-4 Social, environmental and economic indicators. Based on DANE (2013), Fedebiocombustibles (2015) and MA (2013).

Environmental dimension

The dynamics of the environmental dimension of the biodiesel production is presented in Figure 3-5. This dimension consists of three balancing loops (B5, B6 and B7) and four reinforcing loops (R5, R7, R8 and R9). In Colombia, crop yield in palm cultivation has changed from 4.1 tons of palm oil per hectare in 1999 to 3.2 in 2013 (Fedepalma 2013). Crop yield is affected, among many others aspects, by agricultural practices, the use of agrochemicals and conservation practices on soil and water (Cramer et al. 2007a; Silva Lora et al. 2011; DANE 2012). The relation between crop yield and the agricultural practices in palm cultivation are displayed in the balancing loop B5. It shows that an increase in land for palm cultivation increases the agrochemicals applied in lands for palm cultivation. This, in turn, increases the crop yield in palm cultivation. An increase in crop yield in palm cultivation reduces the palm cultivation requirement which in turn decreases the demand of new lands for palm cultivation.

Regarding the relations between indirect and direct land use change associated to palm cultivation, mentioned in social dimension, the reinforcing loop R5 shows that an increase in land for palm cultivation promotes a decrease in agricultural land and, indirectly, an increase in livestock land. The increment in livestock land promotes the decrease in forests and ecosystem lands. If the forest and ecosystem lands are reduced, there will be a reduction in the biodiversity indicator (refer to reinforcing loop R7).

The biodiversity and forest land promote soil conservation, thus a decrease in forest land increase soil loss in palm cultivation. Additionally, if soil loss diminishes the crop yield in palm cultivation will increase (Groom, Gray, and Townsend 2008; Galic et al. 2012). Consequently, a decrease in crop yield increases the demand for land to satisfy the local requirement of palm oil (refer reinforcing loop R5).

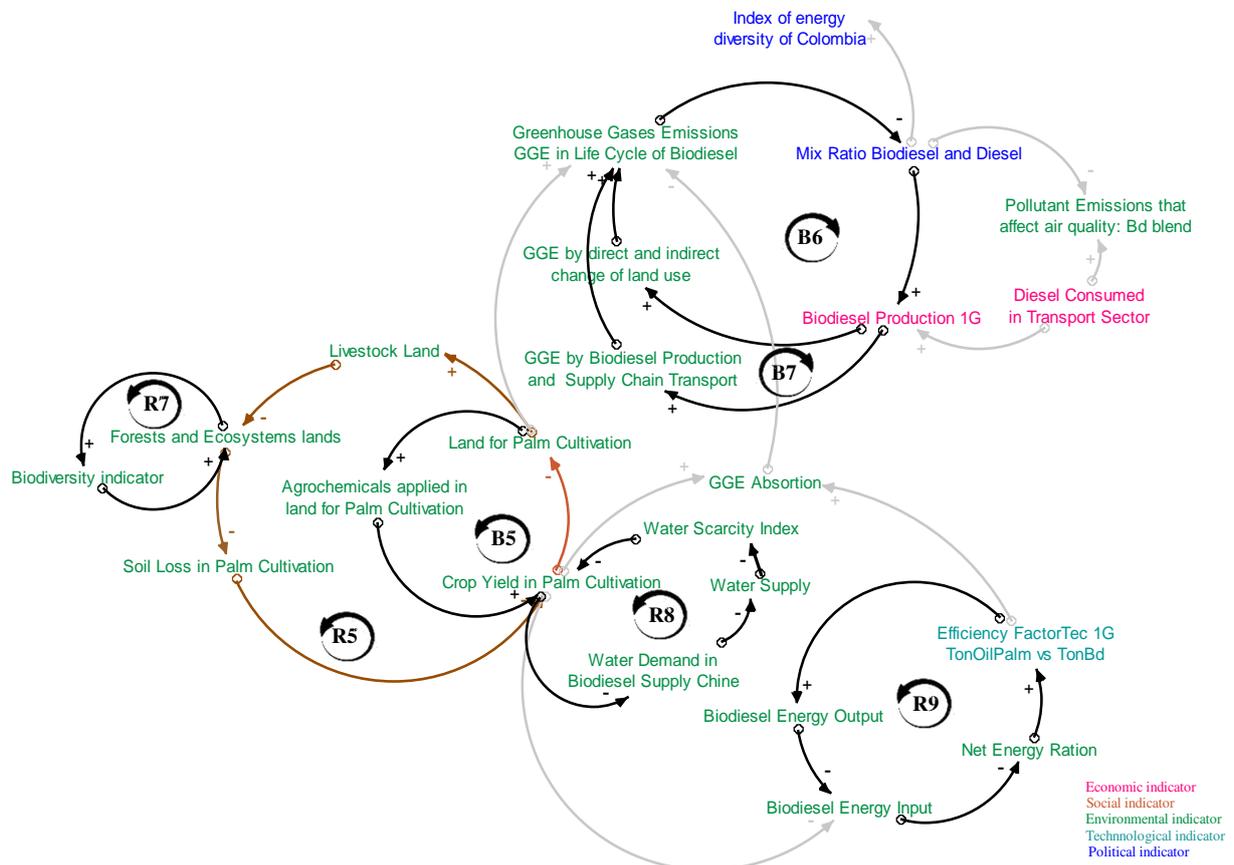


Figure 3-5 Causal loop diagrams of the environmental dimension

The greenhouse gas (GHG) balance during life cycle of biodiesel production includes the stages in the supply chain that emit GHG and the GHG absorption in the palm cultivation. The balancing loop B6 shows that an increase in biodiesel production increases the GHG by direct and indirect land use change. The increment in GHG during the life cycle of biodiesel disesteems to increase the mix ratio biodiesel - diesel (currently the mix ratio in Colombia is about B10). If the mix ratio does not increase biodiesel production is disesteemed too. Likewise, the balancing loop B7 shows that an increase in biodiesel production increases the GHG in the entire life cycle of biodiesel.

Taking a look of the impact of biodiesel production on the water resource, the reinforcing loop R8 in Figure 3-5 shows that an increment in the crop yield promotes the reduction of water demand in the biodiesel supply chain. If water demand increases water supply will diminish

and, consequently, the water scarcity index will increase. An increment in the water scarcity generates a reduction in the crop yield. Regarding the energy balance, reinforcing loop R9 shows that increments in the efficiency technological factor (tons of palm oil per tons of biodiesel produced) and in crop yield, increase biodiesel energy output and decrease energy input. If energy output increases and energy inputs decrease there will be an increment in net energy ratio for biodiesel production.

Technological dimension

The causal loop diagrams of technological dimension are presented in Figure 3-6, which shows that there are two balancing loops B1 and B2, previously identified in the economic dimension related to the valorization of glycerol through PDO production, and one new balancing loop (B8). The reinforcing loop R9 in Figure 3-6 is the same identified in the environmental dimension.

Regarding the valorization of glycerol through PDO production additionally to the previous description, it is considered that if the mix ratio biodiesel - diesel increase is higher than 12%, the PDO production will be an attractive market for biodiesel producers. This assumption is based on the reflection conducted in Bioenergy Technology 2030: Roadmap for Colombia (Gonzalez et al. 2014). By including the valorization of glycerol in the technological dimension is intended to underline the importance of develop alternatives to reuse and manage properly biodiesel industry by-products on the biodiesel profit.

Within the technological dimension a promotion factor of second and third generation biodiesel production in Colombia was defined. This factor considers the World production of second and third generation biodiesel, the number of patents assigned and the number of articles published in scientific journals about biodiesel production of second and third generation (Daim et al. 2006). Balancing loop B8 shows that an increase in the promotion factor increases biodiesel production of second and third generation in Colombia, increasing the total biodiesel production. Equally, an increase in first generation biodiesel production increases the total biodiesel production which decreases the unsatisfied demand of biodiesel.

biodiesel politic (based on UPME (2014)), the mix ratio biodiesel - diesel, and the biodiesel price. The index of energy diversity of Colombia considers the influence of the biodiesel production in the diversity of total primary and secondary energy supply (Herfindahi index) (IEA 2011b).

The political indicators are displayed in balancing loops B6 and B7, described previously in environmental dimension. It is important highlight that an increase in the support of the Colombian government through the costs linked to biodiesel politic, corresponds to an investment because it increases the biodiesel production capacity and its production.

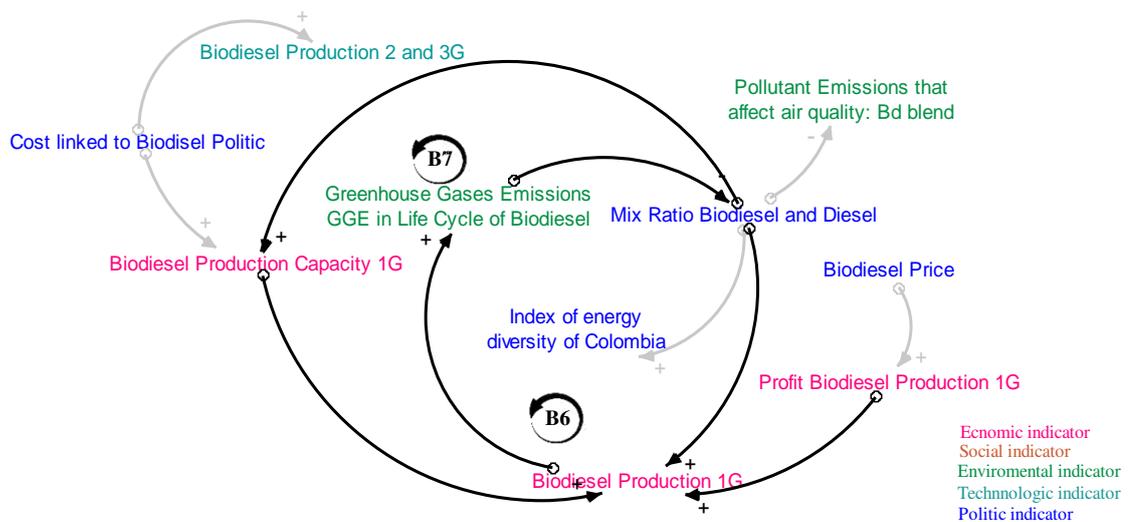


Figure 3-7 Causal loop diagrams of the political dimension

Integrated causal loop diagram

The objective to define an integrated causal loop diagram in Figure 3-8 is shown the interrelationships between the indicators linked to the five sustainable dimensions considered in the assessment framework. The diagram integrates describes a general approach to the complexity of the biodiesel production system in Colombia.

Furthermore, this integrated diagram permits to highlight that the most of causal loops are composed of indicators of different sustainability dimensions. That is according to the discussion exposed in Chapter 2, section 2.6, where interdimensional principles and criteria were found, and attracted attention to the possibility of assessing two or more sustainability dimensions through one criterion and theirs indicators associated.

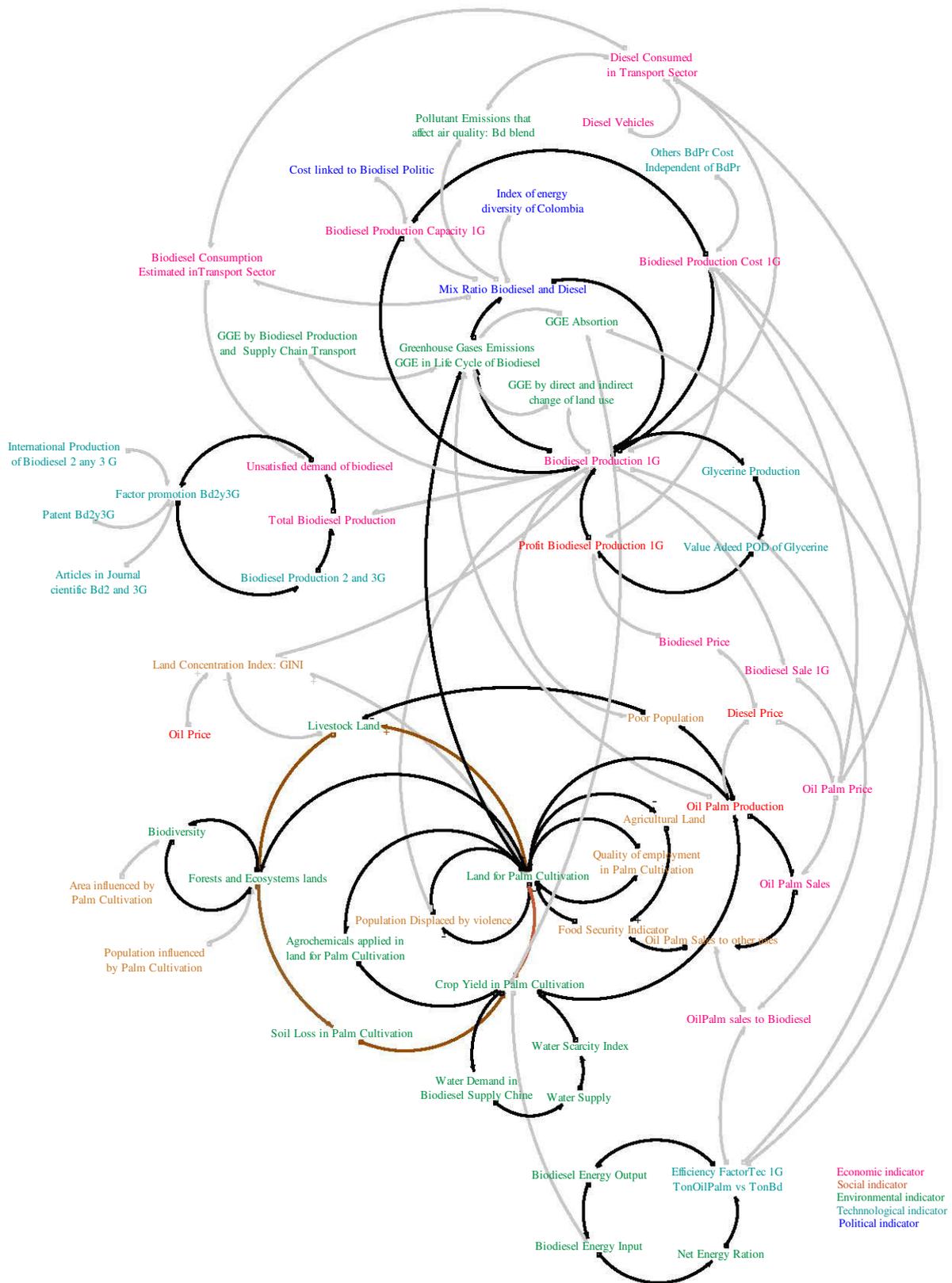


Figure 3-8 Causal loop diagram integrated

Having described the articulation of the problem and conceptualization for the five sustainability dimensions the dynamic hypothesis formulation (model boundary, structure and equations) is discussed in the subsequent section.

3.4.3 Description of the model boundary

Colombian biodiesel production is principally developed in three geographical regions (north, east and central), where the most of the land for palm cultivation is found. Considering this geographical restriction, the impact of biodiesel production on sustainability is analyzed in these three regions. In the Table 3-1 and Table 3-2 the endogenous and exogenous indicators are described. They are part of dynamic hypothesis and show the model boundary.

Endogenous indicators are calculated through of equations (according to methodology description in section 3.3.4), while exogenous indicators are defined by external conditions, and they can be represented by constants, time-depend or graphical functions.

Table 3-1 Endogenous indicators

#	Endogenous	Symbol
1	Biodiesel production of first generation in Colombia	BdPr1G
2	Biodiesel Sale first generation in Colombia	BdSale
3	Biodiesel production capacity first generation	BdPrCap
4	Profit biodiesel production first generation	ProfitBdPr
5	Biodiesel price	BdPrice
6	Diesel price (price of diesel and biodiesel blended)	Dprice
7	Biodiesel production costs first generation	BdPrCosts
8	Others biodiesel production costs depend of biodiesel production	OthBdPrCostsDepPr
9	Biodiesel production costs linked to Palm oil Price	BdPrCostsPalmOilPrice
10	Palm oil price	PalmOilPrice
11	Diesel consumed in transport sector	DiConsTransp
12	Biodiesel consumption estimated in transport sector	BdConsTransp
13	Valorization of glycerol by PDO	PDOGly
14	Glycerol production	GlyPr
15	Factor valorization PDO	FactorValorizPDO
16	Total biodiesel production	TotalBdPr
17	Biodiesel production second and third generation in Colombia	Bd2&3G
18	Unsatisfied demand of biodiesel in Colombia - stock	UnsDemandBd
19	Promotion factor biodiesel second and third generation in Colombia	FactPromBd2&3G
20	Index of energy diversity of Colombia	IndexEnDiv
21	Palm oil production	PalmOilPr
22	Palm oil sales	PalmOilS
23	Palm oil sales to other uses	PalmOilSoth
24	Palm oil sales to biodiesel	PalmOilStoBd
25	Crop yield in palm cultivation	CrYieldPalm
26	Agrochemicals applied in land for palm cultivation	AgrochemPalm
27	Soil loss in palm cultivation	SoilLossPalm
28	Land for palm cultivation	LandP
29	Variation of land for palm cultivation	VarLandP
30	Decrease of land for palm cultivation	DecreaseLandP
31	Agricultural lands	AgrLand
32	Food security indicator	FoodSecInd
33	Variation of agricultural lands	VarAgrLand
34	Livestock land	LivLand
35	Forest and ecosystems lands	ForEcosLand
36	Variation of forest and ecosystems lands	VarForEcosLand
37	Biodiversity indicator	BiodivInd
38	Quality of employment in palm cultivation	QualEmPalm
39	Better quality employment in palm cultivation	BetterQEmPalm
40	Total Workers in Palm Cultivation	TotEmPalm
41	Direct contracts employers in Palm Cultivation	DirectEmPalm
42	Unionized employees in Palm Cultivation	UnionizedEmPalm

#	Endogenous	Symbol
43	Detriment of quality employment in palm cultivation	DetrimQEmPalm
44	Subcontracted employers in Palm Cultivation	SubcontrEmPalm
45	Child Labour in Palm Cultivation	ChildLabPalm
46	Population displaced by violence	PopDispViol
47	Poor population	PoorPop
48	Land concentration index – GINI	GINI
49	Biodiesel energy inputs	BdEnInputs
50	Energy Palm oil extraction	EnPalmOilExtr
51	Input Energy Fertilizers	EnFertilizers
52	Input Energy Palm Cultivation	EnPalmOilCult
53	Energy Transesterification	EnTransect
54	Biodiesel energy output	BdEnOutputs
55	Biodiesel energy	EnBd
56	Palmist cake energy	EnPalmistCake
57	Palmist oil energy	EnPalmistOil
58	Soaps energy	EnSoaps
59	Glycerol purified energy	EnGlycerol
60	Shell energy	EnShell
61	Net energy ration	NER
62	Water demand in geographical regions influenced by biodiesel supply chain	WaterBdSC
63	Agricultural water demand	WaterAgr
64	Water demanded in oil palm cultivation	WaterP
65	Water demanded by palm oil extraction	WaterPalmOilEx
66	Livestock water demand	WaterLiv
67	Population water demand	WaterPop
68	Water demand by biodiesel production	WaterBdPr
69	Water scarcity index	WaterSI
70	GHG by oil palm cultivation and palm oil extraction	GHGP&POE
71	GHG Absorption in oil palm cultivation	GHGabs
72	Oil palm cultivation for biodiesel production	LandP_Bd
73	GHG emissions by indirect change of land use	GHGILUC
74	GHG emissions by direct change of land use	GHGDLUC
75	GHG by biodiesel production and supply chain transport	GHGBdPr&Transp
76	GHG emissions in life cycle of biodiesel	GHGinLCBd
77	Greenhouse gas Emissions if Diesel 100% is used	GHGifDiesel
78	Percentage GHG emissions saving compared with diesel petrochemical used	%GHGsaving
79	Carbon monoxide (CO) emissions of biodiesel blended by diesel	COEmissions
80	Factor driving CO emissions change	FDCO
81	Particulate matter (PM) emission of biodiesel blended by diesel	PMemissions
82	Factor driving PM emissions change	FDPM
83	Hydrocarbons (HC) emission of biodiesel blended by diesel	HCEmissions
84	Factor driving HC emissions change	FDHC
85	Nitrogen oxides (NOx) of biodiesel blended by diesel	NOxEmissions
86	Factor driving NOx emissions change	FDNOx
87	Pollutant Emissions that affect air quality: Biodiesel blend	PEAirQBdDi
88	Carbon monoxide (CO) emissions of diesel 100%	COEmissionsDi
89	Particulate matter (PM) emission of diesel 100%	PMemissionsDi
90	Hydrocarbons (HC) emission of diesel 100%	HCEmissionsDi
91	Nitrogen oxides (NOx) of diesel 100%	NOxEmissionsDi
92	Pollutant Emissions that affect air quality: if Diesel 100%	PEAirQifDiesel100%

Table 3-2 Exogenous indicators

#	Exogenous	Symbol	Type	Value	Units	Notes/Source
1	Mix ratio biodiesel - diesel	MxRtBdDi	Time-dependent function	Current situation Equation 3-2	Dimensionless (v/v)	Used in Chapter 4-Baseline scenario
2	Cost linked to biodiesel politics	CostBdPol	Graphical function	Current situation Figure 3-10	USD	Estimated based on UPME (2014)

#	Exogenous	Symbol	Type	Value	Units	Notes/Source
3	Other biodiesel production costs independent of biodiesel production	OthBdPrCostIndPr	Graphical function	Figure 3-11	USD	Estimated based on Equation 3-10
4	Efficiency Factor Technological biodiesel first generation tons palm oil per tons of biodiesel	EffFactTecPalmOilBd	Constant	1.02	(t Palm Oil)/(t Biodiesel)	Estimated based on Oh et al. (2012); Cadavid et al. (2013)
5	Diesel vehicles	Diesel_Vehicles	Time-dependent function	Current situation Equation 3-14	Dimensionless	Estimated based on MinTransporte (2014)
6	Technological Factor PDO	TFPDO	Constant	0.4	$\frac{t \text{ POD}}{t \text{ Glycerol}}$	(Posada et al. 2013)
7	PDO profitability	PDOprof	Constant	0.677	$\frac{USD}{t \text{ POD}}$	(Posada et al. 2013)
8	International biodiesel production of second and third generation	IntBdPr2&3G	Graphical function	Figure 3-12	t	Estimated based on Biofuels (2014) and IEA (2011a)
9	Patent about second and third generation of biodiesel production	Patent_Bd2&3G	Time-dependent function	Equation 3-21	Dimensionless	Estimated based on patent database Orbit v1.9.4 (ORBIT 2015)
10	Articles in scientific journal about 2 nd and 3 rd generation of biodiesel production	Articles_Bd2&3G	Time-dependent function	Equation 3-22	Dimensionless	Estimated base on SCOPUS consultation (Elsevier 2015)
11	Factor Agrochemical applied in land for palm cultivation	FAAPC	Constant	22	$\frac{t \text{ agrochemicals}}{ha \text{ LandP}}$	(BID and MME 2012a)
12	Decrease factor of oil palm cultivation by second and third generation biodiesel production	FDBd2&3Gha	Constant	1.0E-6	Dimensionless	Estimated based on Technology roadmap (IEA 2011a)
13	Factor biodiversity	FB	Constant	11107	Species of flora and fauna	Estimated based of the amount of species reported in 2007 in a representative region in Colombia (Departamento del Meta) influenced by oil palm cultivation (Instituto Humboldt 2014)
14	Area influenced by oil palm cultivation	AreaInflPalm	Constant	32304200	ha	Estimated based on Colombians political and administrative division that include lands for oil palm cultivations (IGAC 2013)
15	Factor Unionized employees in palm cultivation	FUE	Constant	0.018	$\frac{\text{Employees unionize}}{\text{Total employees}}$	Estimated in this study based on Ministerio de Agricultura de Colombia, (Fedesarrollo 2009), (Vargas 2012)
16	Factor subcontracted employers in palm cultivation	FSCE	Constant	0.75	$\frac{\text{Employees subcont}}{\text{Total employees}}$	
17	Factor of child labour in palm cultivation	FCLPC	Constant	0.012	$\frac{\text{Child labour}}{\text{Total employees}}$	
18	Factor Direct contracts employees in palm cultivation	FDCE	Constant	0.25	$\frac{\text{Direct contracts employ}}{\text{Total employees}}$	
19	Factor total employees in palm cultivation	FTEPC	Constant	0.27	$\frac{\text{Total employees}}{ha \text{ palm cultivation}}$	
20	Number of accidents and occupational diseases	Accid&disease	Time-dependent function	Equation 3-51	Dimensionless	Estimated based on information on safety at work and health risks in the workplace (FASECOLDA and SGRP 2013).
21	Oil price	OilPrice	Graphical function	Figure 3-14	USD/t	Based on EIA (2015)
22	Population influenced by palm cultivation	PopPalm	Time-dependent function	Equation 3-43	Dimensionless	(DANE 2014)
23	Irrigation water Energy		Constant	2.65	GJ/ha	(Yáñez Angarita et al. 2009)
24	Herbicide Energy		Constant	0.56	GJ/ha	(Yáñez Angarita et al. 2009)

#	Exogenous	Symbol	Type	Value	Units	Notes/Source
25	Nitrogen Applied		Constant	0.12	t Nitrogen/ha	The central region in Colombia is the regions that use the most amounts of agrochemicals. This is the reason to use their fertilizers consumes (BID and MME 2012a)
26	Nitrogen Energy		Constant	69.53	GJ/t Nitrogen	(Yee et al. 2009)
27	Phosphate Energy		Constant	7.7	GJ/t Phosphate (P ₂ O ₅)	(Yee et al. 2009)
28	Phosphate Applied		Constant	0.07	t Nitrogen/ha	(BID and MME 2012a)
29	Boron Energy		Constant	0.18	GJ/ha	(de Souza et al. 2010)
30	Potassium Energy		Constant	6.4	GJ/t Potassium (K ₂ O)	(Yee et al. 2009)
31	Potassium applied		Constant	0.30	t Nitrogen/ha	(BID and MME 2012a)
32	Magnesium Energy		Constant	0.14	GJ/ha	(de Souza et al. 2010)
33	Diesel for start up		Constant	0.9	GJ/ha	(de Souza et al. 2010)
34	Steam from power plant		Constant	30.24	GJ/ha	(Yáñez Angarita et al. 2009)
35	Electricity from grid		Constant	0.02	GJ/ha	(de Souza et al. 2010)
36	Electricity from power plant		Constant	2.26	GJ/ha	(Yáñez Angarita et al. 2009)
37	Allocation Kernel oil Kernel cake glycerol coproduct: Energy input		Constant	35.5	GJ/ha	(de Souza et al. 2010)
38	Energy by Transportation		Constant	1.93	GJ/ha	(Yáñez Angarita et al. 2009)
39	Steam in transesterification		Constant	6.58	GJ/ha	(Yáñez Angarita et al. 2009)
40	Methanol		Constant	19.96	GJ/ha	(Yáñez Angarita et al. 2009)
41	Catalyst NaOH		Constant	0.79	GJ/ha	(de Souza et al. 2010)
42	Electricity from grid in transesterification		Constant	0.85	GJ/ha	(Yáñez Angarita et al. 2009)
43	Factor Glycerol purified energy	FGPE	Constant	25.3	GJ/ t Palm oil	(BID and MME 2012a)
44	Factor Soaps Energy	FSE	Constant	37	GJ/ t Palm oil	(BID and MME 2012a)
45	Factor Biodiesel Energy	FBdE	Constant	37.2	GJ/t Biodiesel	(BID and MME 2012a)
46	Factor Shell Energy	FShE	Constant	16.8	GJ/ t Palm oil	(BID and MME 2012a)
47	Factor Palmist Oil Energy	FPmE	Constant	19.1	GJ/ t Palm oil	(BID and MME 2012a)
48	Factor Palmist Cake Energy	FPcE	Constant	19.1	GJ/ t Palm oil	(BID and MME 2012a)
49	Factor water demand by palm cultivation	FWDPC	Constant	3.9E-03	$\frac{Mm^3}{ha}$	(IDEAM 2014)
50	Factor Livestock water demand	FLWD	Constant	4.1E-03	$\frac{Mm^3}{ha}$	(IDEAM 2014)
51	Factor Agricultural Water Demand	FAWD	Constant	2.4E-03	$\frac{Mm^3}{ha}$	(IDEAM 2014)
52	Factor Population Water Demand	FPWD	Constant	4.4E-05	$\frac{Mm^3}{ha}$	(IDEAM 2014)
53	Factor water demanded by palm oil extraction	FWDOPE	Constant	2.2E-07	$\frac{Mm^3}{t}$	(BID and MME 2012a)
54	Factor water demand by biodiesel production	FWDBP	Constant	2.7E-07	$\frac{Mm^3}{t}$	(BID and MME 2012a)
55	Water supply	WaterSup	Constant	6.1E09	Mm ³	Estimated through Equation 3-78
56	Factor water supply	FWS	Constant	189216	$\frac{Mm^3}{ha\ year}$	The original factor is 0.6Mm ³ /km ² s (FAO 2014) as water supply in average year in Colombia.
57	Ecological flows	EcolFl	Constant	6.1E08	Mm ³	Estimated based on (IDEAM 2014) as 10% of water supply
58	Factor ecological flows	FEF	Constant	0.1	Dimensionless	(Castanheira, Acevedo, and Freire 2014)
59	Factor GHG in oil palm cultivation and palm oil extraction	FGHGP&POE	Constant	0.55	$\frac{t\ CO_{2-eq}}{t\ Oil\ Palm}$	(Castanheira, Acevedo, and Freire 2014)

#	Exogenous	Symbol	Type	Value	Units	Notes/Source
60	GHG absorption factor	FAGHG	Constant	22.83	$\frac{t CO_2-eq}{ha}$	Estimated based on the indicator oil palm fresh fruit bunches (FFB): and (BID and MME 2012a)
61	Land use change of forest to palm cultivation	LUCF	Constant	0.23	Dimensionless	Types of land palm is expands onto in the marginal producing in Colombia in 2020 (based on Winrock data for the US EPA(2010) reported in (Bauen et al. 2010))
62	Land use change of grass to palm cultivation	LUCG	Constant	0.09	Dimensionless	
63	Land use change of mix to palm cultivation	LUCM	Constant	0.31	Dimensionless	
64	Land use change of savannah to palm cultivation	LUCS	Constant	0.18	Dimensionless	
65	Land use change of shrub to palm cultivation	LUCSh	Constant	0.08	Dimensionless	
66	Land use change of wetland to palm cultivation	LUCW	Constant	0.01	Dimensionless	
67	Land use change of barren to palm cultivation	LUCB	Constant	0.01	Dimensionless	
68	GHG factor linked to LUC of forest to palm cultivation	GHGFF	Constant	126	$\frac{t CO_2-eq}{ha}$	GHG emissions by direct land use change to palm in Colombia (based on Winrock data for the US EPA(2010) reported in (Bauen et al. 2010)), considering 100 year emission factor.
69	GHG factor linked to LUC of grass to palm cultivation	GHGFG	Constant	-28	$\frac{t CO_2-eq}{ha}$	
70	GHG factor linked to LUC of mix to palm cultivation	GHGFM	Constant	10.7	$\frac{t CO_2-eq}{ha}$	
71	GHG factor linked to LUC of savannah to palm cultivation	GHGFS	Constant	-22	$\frac{t CO_2-eq}{ha}$	
72	GHG factor linked to LUC of shrub to palm cultivation	GHGFSh	Constant	-10	$\frac{t CO_2-eq}{ha}$	
73	GHG factor linked to LUC of wetland to palm cultivation	GHGFW	Constant	-19	$\frac{t CO_2-eq}{ha}$	
74	GHG factor linked to LUC of barren to palm cultivation	GHGFB	Constant	0	$\frac{t CO_2-eq}{ha}$	
75	GHG factor linked to indirect LUC	GHGFILUC	Constant	0.04	$\frac{t CO_2-eq}{t Biodiesel}$	Estimated based on ILUC factor breakdown in Colombia (Bauen et al. 2010) and (BID and MME 2012a)
76	GHG factor in biodiesel production and supply chain transport	GHGFBdPr&Transp	Constant	1.19	$\frac{t CO_2-eq}{t Biodiesel}$	Estimated based on ILUC factor breakdown in Colombia (Bauen et al. 2010) and (BID and MME 2012a)
77	GHG factor in life cycle of diesel in Colombia	GHGFLCD	Constant	3.57	$\frac{t CO_2-eq}{t Diesel}$	(BID and MME 2012a)
78	CO emission factor of diesel	FCODiesel	Constant	0.017	$\frac{t CO}{t Diesel}$	Estimate based on emission factor of the Colombian diesel production (BID & MMEC 2012)
79	PM emission factor of diesel	FPMDiesel	Constant	5.5E-07	$\frac{t PM}{t Diesel}$	
80	HC emission factor of diesel	FHCDiesel	Constant	1.8E-03	$\frac{t HC}{t Diesel}$	
81	NOx emission factor of diesel	FNOxDiesel	Constant	6.3E-02	$\frac{t NOx}{t Diesel}$	

3.4.4 Description of the model structure and equations

The dynamic model was divided into six sub-models. These sub-models represent the interactions between economic, social, environmental, politic and technological dimensions for

the biodiesel production, according to the framework presented in Chapter 2. It is noted that the names of sub-models not conform to sustainability dimensions. Due to the strong interactions of dimensions (shows on data visualization in Figure 2-19), and also as a result of causal loop diagram, consequently six main sub-models emerged. The sub-models are: biodiesel production, land and social, net energy ratio, water demand, greenhouse gas emissions saving in life cycle of biodiesel, and pollutant emission that affect air quality as a consequence of the use of biodiesel - diesel blends as biofuel. Each sub-model and the equations of the selected indicators are described in the subsequent sections.

- Biodiesel production sub-model

This sub-model is composed of six stocks and flows (S&F): biodiesel production of first generation (1G), biodiesel production capacity, profit of first generation biodiesel production, valorization of glycerol by PDO, total biodiesel production, and unsatisfied demand of biodiesel in Colombia. The equations that describe each S&F are shown in Table 3-3, Figure 3-10, Figure 3-11 and Figure 3-12. The graphical S&F is presented in Figure 3-9. The equation constants are displayed in the Appendix 2 and the statistical issues of equations definition are described in the Appendix 3. The endogenous and exogenous indicators used in each equation are described in Table 3-1 and Table 3-2, respectively.

In Colombia, biodiesel production started in 2008, but the model includes the SD from 1999. Then, the year for the model initial time (time zero) is 1999 and the biodiesel production begins in time= 8.

Table 3-3 Stock and flow equations by biodiesel production sub-model

#	S&F	Equation	Indicator
1	Biodiesel production of first generation in Colombia	Equation 3-1 $BdPr1G = \text{if time} > 8 \text{ then } (A1 \times MxRtBdDi - A2 \times BdPrCosts < BdPrCap \text{ then } A1 \times MxRtBdDi - A2 \times BdPrCosts \text{ else } BdPrCap) \text{ else } 0$	Endogenous
		Equation 3-2 $MxRtBdDi = \text{if time} > 8 \text{ then } -A1 + A2 \times \text{time} \text{ else } 0$	Exogenous
		Equation 3-3 $BdSale = A1 \times BdPr1G$	Endogenous
2	Biodiesel production capacity	Equation 3-4 $BdPrCap = \text{If time} > 8 \text{ then } A1 \times CostBdPol \text{ else } 0$	Endogenous
		$CostBdPol$ refer graphical function in Figure 3-10	Exogenous
3	Profit of first generation biodiesel production	Equation 3-5 $ProfitBdPr = BdPrice - BdPrCosts + PODGly$	Endogenous
		Equation 3-6 $BdPrice = \text{if time} > 8 \text{ then } A1 + A2 \times PalmOilPrice \text{ else } 0$	Endogenous
		Equation 3-7 $\text{if time} > 8 \text{ then } [BdPrCosts = OthBdPrCostIndPr + OthBdPrCostsDepPr + BdPrCostsPalmOilPrice] \text{ else } [BdPrCosts = 0]$	Endogenous
		Equation 3-8 $Dprice = A1 \times BdPrice + A2 \times OilPrice$	Endogenous
		$OilPrice$ refer graphical function in Figure 3-14	Exogenous
		$OthBdPrCostIndPr$ refer graphical function in Figure 3-11	Exogenous
		Equation 3-9 $\text{if time} > 8 \text{ then } [OthBdPrCostDepPr = A1 \times AccumPrBd^{-A2}] \text{ else } [OthBdPrCostDepPr = 0]$	Endogenous (equation defined)

#	S&F	Equation	Indicator
		Where $AccumPrBd = AccumPrBd(t - dt) + (BdPr1G) \times dt$ INIT AccumPrBd = 22730 t Biodiesel INIT=Initial value is the Colombian biodiesel production in 2008	based on de Wit et al. (2010))
		Assumption a minimal profit of biodiesel production of 0.1(BdPrice), then Equation 3-10 $OthBdPrCostIndPr = ProfitBdPr - OthBdPrCostsDepRr - BdPrCostPalmOilPrice$	Exogenous
		Equation 3-11 If time > 8 then $[BdPrCostPalmOilPrice = EffFactTecPalmOilBd \times PalmOilPrice]$ else $[BdPrCostPalmOilPrice = 0]$	Endogenous
		$EffFactTecPalmOilBd = 1.02$	Exogenous
		Equation 3-12 $PalmOilPrice = A1 + A2 \times OilPrice + A3 \times PalmOilStoBd$	Endogenous
		PalmOilStoBd refer Equation 3-29	Endogenous
		Equation 3-13 $DiConsTransp = A1 \times Diesel_Vehicles$	Endogenous
		Equation 3-14 $Diesel_Vehicles = A1 + A2 \times time$	Exogenous
4	Valorization of glycerol by PDO	Equation 3-15 $PDOGly = GlyPr \times FactorValorizPDO \times TFPDO \times PODprof$	Endogenous
		Equation 3-16 $GlyPr = A1 \times BdPr1G$	Endogenous
		Equation 3-17 If $MixRtBdDi > 0.12$ then $[FactorValorizPDO = MixRtBdDi + MixRtBdDi \times 0.1]$ else $[FactorValorizPDO = 0]$	Endogenous
		$TFPDO = 0.4$	Exogenous
		$PDOprof = 0.677$	Exogenous
5	Total biodiesel production	Equation 3-18 $TotalBdPr = BdPr1G + Bd2\&3G$	Endogenous
		Equation 3-19 If time ≥ 20 then $[Bd2\&3G = BdPr1G \times 0.10 + FactPromBd2\&3G]$ else $[Bd2\&3G = 0]$	Endogenous
		Equation 3-20 $FactPromBd2\&3G = \left(\frac{Patent_Bd2\&3G}{Articles_Bd2\&3G} \right) \times IntBdPr2\&3G + \left(\frac{SkUnsDemandBd}{100} \right)$	Endogenous
		Equation 3-21 $Patent_Bd2\&3G = A1 + \frac{(A2-A3)}{1 + \exp\left(\frac{(time-A4)}{A5}\right)}$	Exogenous
		Equation 3-22 $Articles_Bd2\&3G = A1 + \frac{(A2-A3)}{1 + \exp\left(\frac{(time-A4)}{A5}\right)}$	Exogenous
		IntBdPr2&3G refer graphical function in Figure 3-12	Exogenous
6	Unsatisfied demand of biodiesel in Colombia	Equation 3-23 $SkUnsDemandBd(t) = SkUnsDemandBd(t - dt) + UnsDemandBd \times dt$ INIT SkUnsDemandBd = 0	Endogenous
		Equation 3-24 $UnsDemandBd = BdConsTransp - TotalBdPr$	Endogenous
		Equation 3-25 $BdConsTransp = \frac{(DieselConsumTransp \times MxRtBdDi)}{(1 - MxRtBdDi)}$	Endogenous
		Equation 3-26 $IndexEnDiv = -A1 \times \cos(MxRtBdDi + A2) + A3 \times \cos(A4 \times MxRtBdDi + A5) + A6$	Endogenous

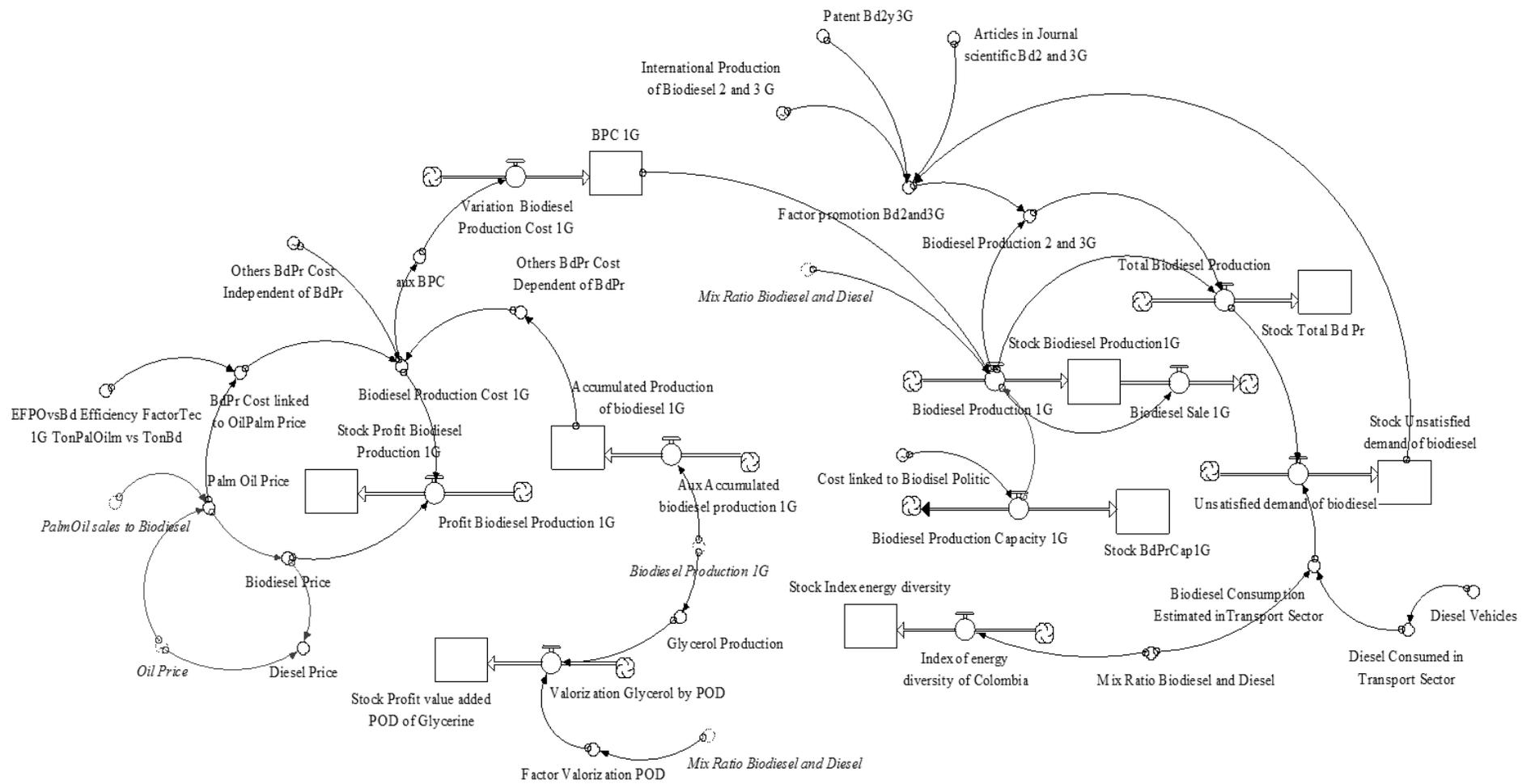


Figure 3-9. Biodiesel production sub-model

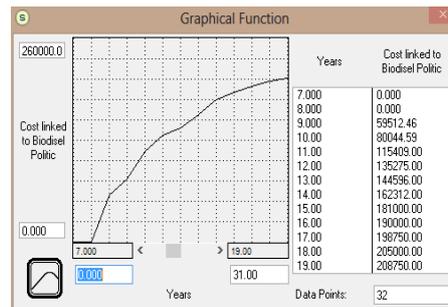


Figure 3-10 Graphical function of cost linked to biodiesel politic in current situation

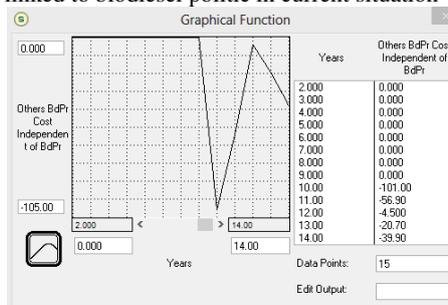


Figure 3-11 Others Biodiesel Production Costs Independent of Biodiesel Production

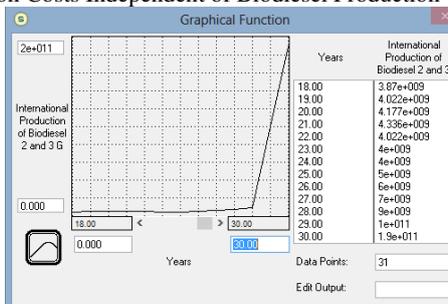


Figure 3-12 Graphical function of international production of biodiesel of second and third generation

In biodiesel production sub-model there are endogenous indicators that could be used in other sub-models, called output indicators. Their description and sub-models of destination are shown in Table 3-4.

Table 3-4 Output indicator from biodiesel production sub-model

Indicator	Symbol	Sub-model of destination
Biodiesel production 1G	BdPr1G	Land and social sub-model Greenhouse gas emission saving in life cycle of biodiesel sub-model Water demanded sub-model
Palm oil price	PalmOilPrice	Land and social sub-model
Biodiesel consumption estimated in transport sector	BdConsTransp	Land and social sub-model
Biodiesel production second and third generation	Bd2&3G	Land and social sub-model
Diesel consumed in transport sector	DiConsTransp	Land and social sub-model Pollutant emission that affect air quality as a consequence of the use of biodiesel - diesel blends as biofuel

- Land and social sub-model

This sub-model is composed of ten S&F: palm oil production, crop yield in palm cultivation, lands for palm cultivation, agricultural lands, livestock lands, forest and ecosystems lands,

employment quality in palm cultivation, population displaced by violence, poor population, and land concentration index: GINI. The equations that describe each S&F are shown in Table 3-5 and Figure 3.14, while the graphical S&F is shown in Figure 3-13. The equation constants are displayed in the Appendix 2 and the statistical issues of equation definitions are describe in the Appendix 3. The endogenous and exogenous indicators used in each equation were described in Table 3-1 and Table 3-2 respectively.

Table 3-5 Stock and flow equations by land and social sub-model

#	S&F	Equation	Indicator
1	Palm oil production	Equation 3-27 $\text{PalmOilPr} = \text{if } (A1 \times \text{CrYieldPalm} + A2 \times \text{DPrice}) < (\text{LandP} \times \text{CrYieldPalm}) \text{ then } (A1 \times \text{CrYieldPalm} + A2 \times \text{DPrice}) \text{ else } (\text{LandP} \times \text{CrYieldPalm})$	Endogenous
		Dprice refer Equation 3-8	
		Equation 3-28 $\text{PalmOilS} = A1 \times \text{PalmOilPr}$	Endogenous
		Equation 3-29 $\text{PalmOilStoBd} = \text{EffFactTecPalmOilBd} \times \text{BdPr1G}$	Endogenous
		BdPr1G refer Equation 3-1, EffFactTecPalmOilBd refer Table 3-2	
		Equation 3-30 $\text{PalmOilSoth} = \text{PalmOilS} - \text{PalmOilStoBd}$	Endogenous
2	Crop yield in palm cultivation	Equation 3-31 $\text{CrYieldPalm} = A1 - A2 \times \text{SoilLossPalm} + A3 \times \text{AgrochemPalm}$	Endogenous
		Equation 3-32 $\text{SoilLossPalm} = A1 \times \text{AgrochemPalm} - A2 \times \text{ForEcosLands}$	Endogenous
		Equation 3-33 $\text{AgrochemPalm} = \text{LandP} \times \text{FAAPC}$	Endogenous
		FAAPC = 22	Exogenous
3	Lands for palm cultivation	Equation 3-34 $\text{LandP}(t) = \text{LandP}(t - dt) + (\text{VarLandP} - \text{DecreaseLandP}) dt$ INIT LandP = 143115 ha	Endogenous
		Equation 3-35 $\text{VarLandP} = -A1 \times \cos(\text{QualEmPalm}) - A2 \times \cos(\text{CrYieldPalm}) + A3 \times \cos(\text{BdConsTransp}) - A4 \times \cos(\text{VarPopDispViol})$	
		Equation 3-36 $\text{DecreaseLandP} = \text{FDBd2\&3Gha} \times \text{BdPr2\&3G}$ $\text{FDBd2\&3Gha} = 1.0^{-6}$	Exogenous
4	Agricultural lands	Equation 3-37 $\text{AgrLand}(t) = \text{AgrLand}(t - dt) + (-\text{VarAgrLand}) dt$ INIT AgrLand = 2068915 ha	Endogenous
		Equation 3-38 $\text{VarAgrLand} = A1 \times \text{AgrLand} - A2 \times \text{LivLand} + A3 \times \text{LandP}$	
		Equation 3-39 $\text{FoodSecInd} = \frac{\text{AgrLand}}{\text{LandP}}$	Endogenous
5	Livestock lands	Equation 3-40 $\text{LivLand} = A1 - A2 \times \text{AgrLand} - A3 \times \text{PoorPop} + A4 \times \text{VarLandP}$	Endogenous
6	Forest and ecosystems lands	Equation 3-41 $\text{ForEcosLand}(t) = \text{ForEcosLand}(t - dt) + (-\text{VarForEcosLand})dt$ INIT ForEcosLand = 13006622 ha	Endogenous
		Equation 3-42 $\text{VarForEcosLand} = -A1 + A2 \times \text{ForEcosLands} - A3 \times \text{LivLand} + A4 \times \text{PopPalm}$	
		Equation 3-43 $\text{PopPalm} = A1 + A2 \times \text{time}$	Exogenous
		Equation 3-44 $\text{BiodivInd} = \frac{(\text{FB} \times \text{ForEcosland})}{\text{AreaInflPalm}}$	Endogenous
		FB = 11107	Exogenous
		AreaInflPalm = 32304200	Exogenous
7	Employment quality in palm cultivation	Equation 3-45 $\text{QualEmPalm} = \text{BetterQEmPalm} - \text{DetrimQEmPalm}$	Endogenous
		Equation 3-46 $\text{BetterQEmPalm} = \text{DirectEmPalm} + \text{UnionizedEmPalm}$	Endogenous
		Equation 3-47 $\text{TotEmPalm} = \text{FTEPC} \times \text{LandP}$	Endogenous

#	S&F	Equation	Indicator
		FTEPC = 0.27	Exogenous
		Equation 3-48 $\text{DirectEmPalm} = \text{FDCE} \times \text{TotEmPalm}$	Endogenous
		FDCE = 0.25	Exogenous
		Equation 3-49 $\text{UnionizedEmPalm} = \text{FUE} \times \text{TotEmPalm}$	Endogenous
		FUE = 0.018	Exogenous
		Equation 3-50 $\text{DetrimQEmPalm} = \text{Accid\&diseases} + \text{SubcontrEmPalm} + \text{ChildLabPalm}$	Endogenous
		Equation 3-51 $\text{Accid\&diseases} = A1 \times \text{time}^3 - A2 \times \text{time}^2 + A3 \times \text{time} + A4$	Exogenous
		Equation 3-52 $\text{SubcontrEmPalm} = \text{FSCE} \times \text{TotEmPalm}$	Endogenous
		FSCE = 0.75	Exogenous
		Equation 3-53 $\text{ChildLabPalm} = \text{FCLPC} \times \text{TotEmPalm}$	Endogenous
		FCLPC = 0.012	Exogenous
8	Population displaced by violence	Equation 3-54 $\text{PopDispViol} = A1 - A2 \times \text{LandP}$	Endogenous
9	Poor population	Equation 3-55 $\text{PoorPop} = A1 - A2 \times \text{LandP}$	Endogenous
10	Land concentration index: GINI	Equation 3-56 $\text{GINI} = A1 - A2 \times \text{LivLand} + A3 \times \text{LandP} + A4 \times \text{OilPrice} - A5 \times \text{DiConsTransp} - A6 \times \text{BdPr1G}$	Endogenous
		OilPrice graphical function in Figure 3-14	Exogenous

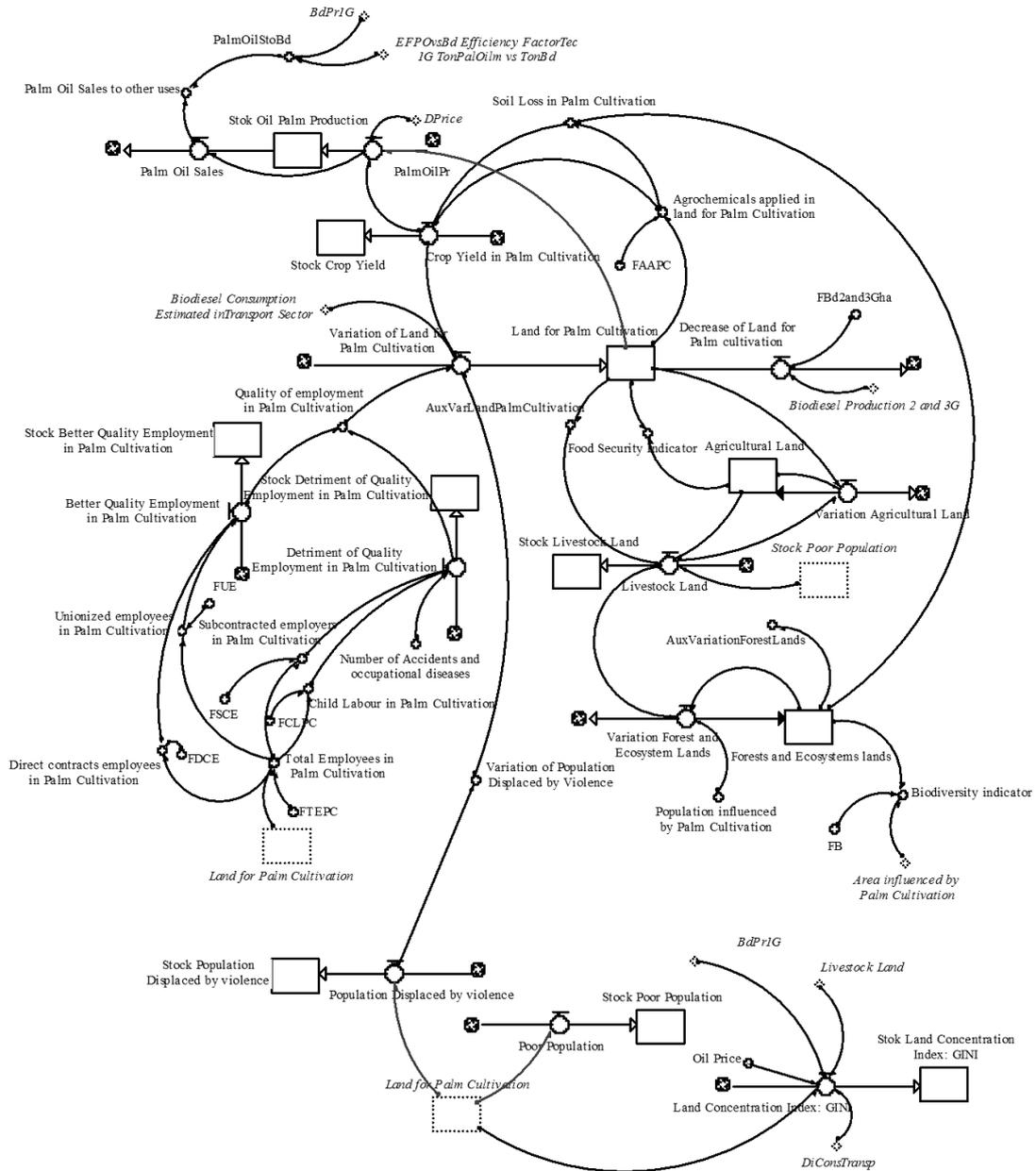


Figure 3-13 Land and social sub-model

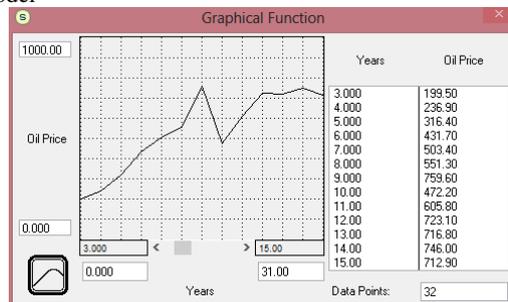


Figure 3-14 Graphical function of oil price based on EIA (2015)

In land and social sub-model there are input indicators that come from of other sub-models (Table 3-6). Furthermore, there are endogenous indicators that could be used in other sub-models, called output indicators. Their description and sub-models of destination are shown in Table 3-7.

Table 3-6 Input indicator used in land and social sub-model

Indicator	Symbol	Sub-model of origin
Biodiesel production 1G	BdPr1G	Biodiesel production sub-model
Biodiesel consumption estimated in transport sector	BdConsTransp	Biodiesel production sub-model
Diesel consumed in transport sector	DiConsTransp	Biodiesel production sub-model
Oil price	OilPrice	Biodiesel production sub-model

Table 3-7 Output indicator from land and social sub-model

Indicator	Symbol	Sub-model destination
Crop yield in palm cultivation	CrYieldPalm	Greenhouse gas emission saving in life cycle of biodiesel sub-model
		Net energy ratio sub-model
Livestock land	LivLand	Water demanded sub-model
Palm oil production	PalmOilPr	Water demanded sub-model
Land for palm cultivation	LandP	Water demanded sub-model
Agricultural land	AgrLand	Water demanded sub-model

- Net energy ratio sub-model

This sub-model is composed of eight S&F: input energy fertilizers, input energy palm cultivation, energy palm oil extraction, input energy transportation, energy transesterification, biodiesel energy input, biodiesel energy output, and net energy ratio. The equations that describe each S&F are shown in Table 3-8, and the graphical S&F is shown in Figure 3-15. The equation constants are displayed in the Appendix 2 and the statistical issues of equation definitions are describe in the Appendix 3. The endogenous and exogenous indicators used in each equation are described in Table 3-1 and Table 3-2 respectively.

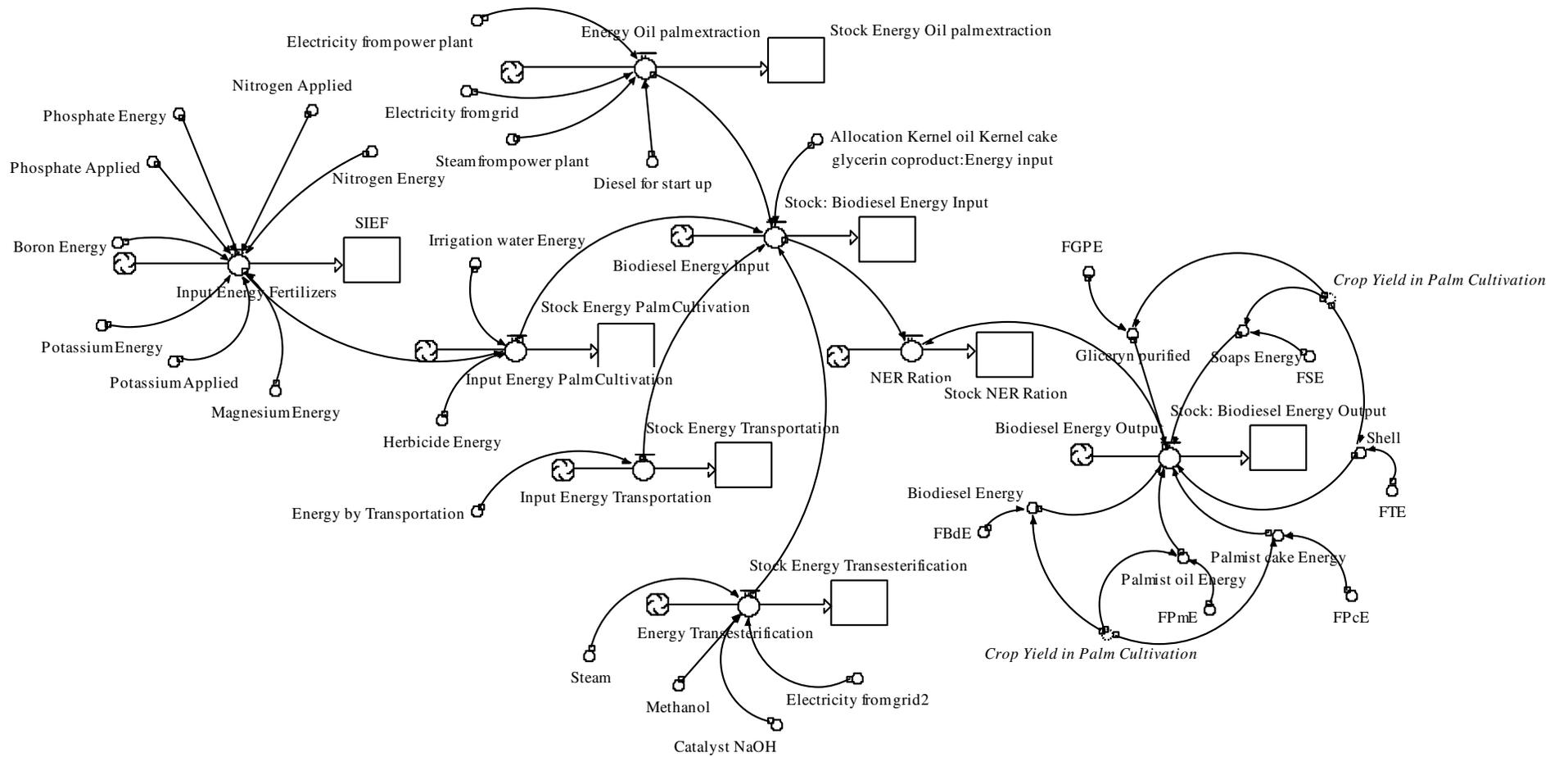


Figure 3-15 Net energy ratio sub-model

Table 3-8 Stock and flow equations by net energy ratio sub-model

#	S&F	Equation	Indicator
1	Input energy fertilizers	<i>Equation 3-57</i> $EnFertilizers = Nitrogen_Applied \times Nitrogen_Energy + Phosphate_Applied \times Phosphate_Energy + Potassium_Energy \times Potassium_Applied + Magnesium_Energy + Boron_Energy$	Endogenous
		$Nitrogen_Applied = 0.12$	Exogenous
		$Nitrogen_Energy = 69.53$	Exogenous
		$Phosphate_Applied = 0.07$	Exogenous
		$Phosphate_Energy = 7.7$	Exogenous
		$Potassium_Energy = 6.4$	Exogenous
		$Potassium_Applied = 0.3$	Exogenous
		$Magnesium_Energy = 0.14$	Exogenous
		$Boron_Energy = 0.18$	Exogenous
2	Input energy palm cultivation	<i>Equation 3-58</i> $EnPalmOilCult = EnFertilizers + EnHerbicides + EnIrrWater$	Endogenous
		$EnHerbicides = 0.56$	Exogenous
		$EnIrrWater = 2.65$	Exogenous
3	Energy palm oil extraction	<i>Equation 3-59</i> $EnPalmOilExtr = DieselStartup + ElectricityGrid + ElectricityPowerPlant + SteamPowerPlant$	
		$DieselStartup = 0.9$	Exogenous
		$ElectricityGrid = 0.02$	Exogenous
		$ElectricityPowerPlant = 2.26$	Exogenous
		$SteamPowerPlant = 30.24$	Exogenous
4	Input energy transportation	$EnTransp = 1.93$	Exogenous
5	Energy transesterification	<i>Equation 3-60</i> $EnTransest = Catalyst_NaOH + Electricity_from_grid2 + Methanol + Steam$	Endogenous
		$Catalyst_NaOH = 0.79$	Exogenous
		$Electricity_from_grid2 = 0.85$	Exogenous
		$Methanol = 19.96$	Exogenous
		$Steam = 6.58$	Exogenous
		$EnKernel\&Glycerin = 35.5$	Exogenous
6	Biodiesel energy input	<i>Equation 3-61</i> $BdEnInputs = EnPalmCult + EnPalmOilExtr + EnTransest + EnTransp + EnKernel\&Glycerin$	Endogenous
7	Biodiesel energy output	<i>Equation 3-62</i> $BdEnOutputs = EnBd + EnPalmistCake + EnPalmistOil + EnSoaps + EnGlycerol + EnShell$	Endogenous
		<i>Equation 3-63</i> $EnBd = FBdE \times CrYieldPalm$	Endogenous
		$FBdE = 37.2$	Exogenous
		<i>Equation 3-64</i> $EnPalmistCake = FPcE \times CrYieldPalm$	Endogenous
		$FPcE = 19.1$	Exogenous
		<i>Equation 3-65</i> $EnPalmistOil = FPmE \times CrYieldPalm$	Endogenous
		$FPmE = 19.1$	Exogenous
		<i>Equation 3-66</i> $EnSoaps = FSE \times CrYieldPalm$	Endogenous
		$FSE = 37$	Exogenous
		<i>Equation 3-67</i> $EnGlycerol = FGPE \times CrYieldPalm$	Endogenous
		$FGPE = 25.3$	Exogenous
<i>Equation 3-68</i> $EnShell = FShE \times CrYieldPalm$	Endogenous		
		$FShE = 16.8$	Exogenous
8	Net energy ratio	<i>Equation 3-69</i> $NER = \frac{BdEnOutputs}{BdEnInputs}$	Endogenous

In the net energy ratio sub-model there is one input indicator that come from of land and social sub-model. It is shown in Table 3-9.

Table 3-9 Inputs indicators used in net energy ratio sub-model

Indicator	Symbol	Sub-model of origin
Crop yield in palm cultivation	CrYieldPalm	Land and social sub-model

- Water demanded sub-model

The water demanded sub-model is composed of two S&F: water demand in region influenced by biodiesel supply chain and water scarcity index. The equations that describe each S&F are shown in Table 3-10, and the graphical S&F is shown in Figure 3-16. The equation constants are displayed in the Appendix 2 and the statistical issues of equation definitions are described in the Appendix 3. The endogenous and exogenous indicators used in each equation are described in Table 3-1 and Table 3-2 respectively.

Table 3-10 Stock and flow equations by water demand sub-model

#	S&F	Equation	Indicator
1	Water demand in geographical regions influenced by biodiesel supply chain	Equation 3-70 $WaterBdSC = WaterP + WaterPalmOilEx + WaterBdPr + WaterPop + WaterLiv + WaterAgr$	Endogenous
		Equation 3-71 $WaterP = LandP \times FWDPC$	Endogenous
		$FWDPC = 3.9E-03$	Exogenous
		Equation 3-72 $WaterPalmOilEx = FWDPE \times PalmOilPr$	Endogenous
		$FWDPE = 2.2E-07$	Exogenous
		Equation 3-73 $WaterBdPr = FWDBP \times BdPr1G$	Endogenous
		$FWDBP = 2.7E-07$	Exogenous
		Equation 3-74 $WaterPop = FPWD \times PopPalm$	Endogenous
		$FPWD = 4.4E-05$	Exogenous
		Equation 3-75 $WaterLiv = FLWD \times LivLand$	Endogenous
		$FLWD = 4.1E-03$	Exogenous
		Equation 3-76 $WaterAgr = AgrLand \times FAWD$	Endogenous
$FAWD = 2.4E-03$	Exogenous		
2	Water scarcity index	Equation 3-77 $WaterSI = \frac{WaterBdSC}{(WaterSup - EcolFl)}$	Endogenous
		Equation 3-78 $WaterSup = FWS \times AreaInflPalm$	Exogenous
		$FWS = 189216$	Exogenous
		$AreaInflPalm = 32304200$	Exogenous
		Equation 3-79 $EcolFl = FEF \times WaterSup$	Exogenous
$FEF = 0.1$	Exogenous		

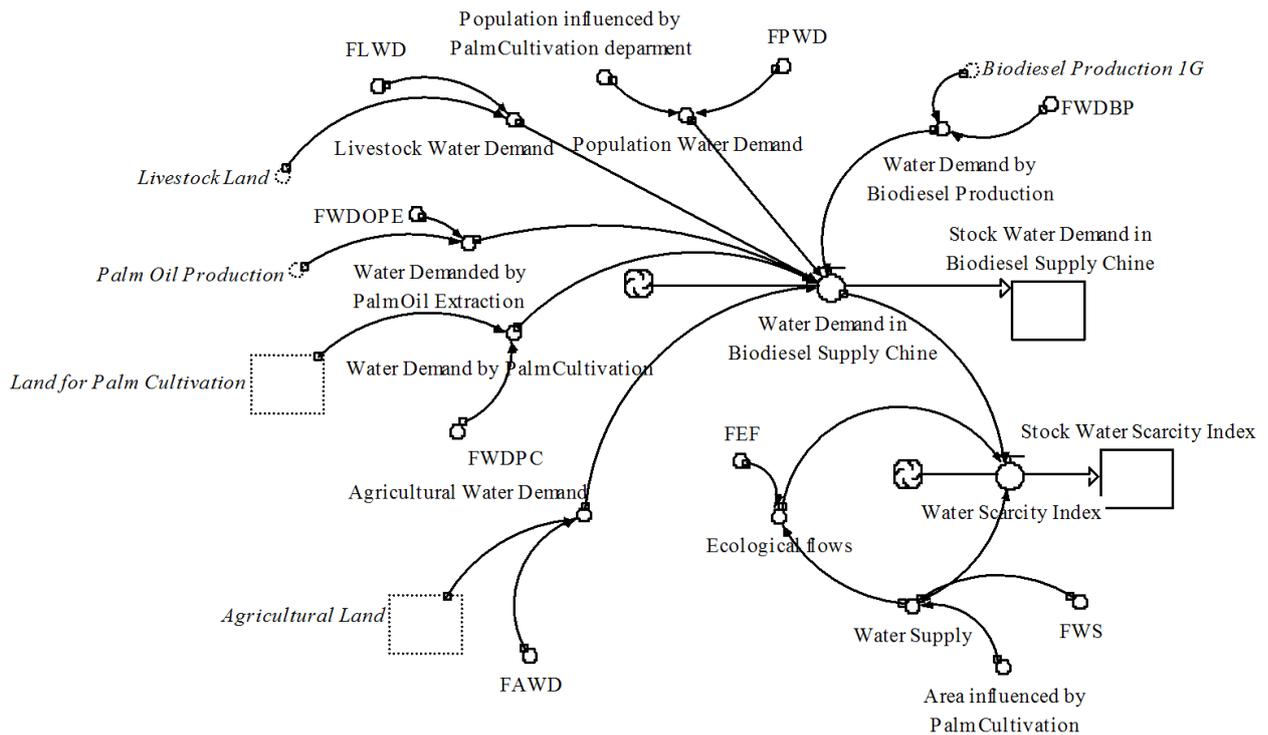


Figure 3-16 Water sub-model

The input indicators used in this sub-model that comes from of other sub-models are shown in Table 3-11.

Table 3-11 Inputs indicators used in water sub-model

Indicator	Symbol	Sub-model of origin
Biodiesel production 1G	BdPr1G	Biodiesel production sub-model
Livestock land	LivLand	Land and social sub-model
Palm oil production	PalmOilPr	
Land for palm cultivation	LandP	
Agricultural land	AgrLand	

- Greenhouse gas emissions saving in life cycle of biodiesel sub-model

This sub-model is composed of seven S&F: greenhouse gas emissions (GHG) by oil palm cultivation and palm oil extraction, GHG absorption by palm cultivation, GHG by indirect change of land use, GHG by direct change of land use, GHG by biodiesel production and supply chain transport, GHG if Diesel 100% is used in Colombian transport sector, and GHG in life cycle of biodiesel. Furthermore, this sub-model estimated the percentage of GHG saving compared with diesel petrochemical used. The equations that describe each S&F are shown in Table 3-12, and the graphical S&F is presented in Figure 3-17.

Table 3-12 Stock and flow equations by GHG emissions saving in life cycle of biodiesel sub-model

#	S&F	Equation	Indicator
1	GHG by oil palm cultivation and palm oil extraction	Equation 3-80 $GHG_{P\&O} = BdPr1G \times FG_{P\&O} \times EffFactTecPalmOilBd$	Endogenous
		$FG_{P\&O} = 0.55$	Exogenous
		$EffFactTecPalmOilBd = 1.02$	Exogenous

#	S&F	Equation	Indicator
2	GHG absorption by palm cultivation	Equation 3-81 $GHG_{abs} = LandP_Bd \times FAGHG$	Endogenous
		Equation 3-82 $LandP_Bd = \text{if } ((BdPr1G \times EffFactTecPalmOilBd)/CropYieldPalm) < LandP \text{ then } ((BdPr1G \times EffFactTecPalmOilBd)/CropYieldPalm) \text{ else } LandP$	Endogenous
		$FAGHG=22.83$	Exogenous
3	GHG by indirect change of land use	Equation 3-83 $GHG_{ILUC} = GHG_{FILUC} \times BdPr1G$	Endogenous
		$GHG_{FILUC} = 0.04$	Exogenous
4	GHG by direct change of land use	Equation 3-84 $GHG_{DLUC} = Landp_Bd \times [LUCF \times GHG_{FF} + LUCG \times GHG_{FG} + LUCM \times GHG_{FM} + LUCS \times GHG_{FS} + LUCSh \times GHG_{FSh} + LUCW \times GHG_{FW} + LUCB \times GHG_{FB}]$	Endogenous
		$LUCF=0.23$	Exogenous
		$GHG_{FF}=126$	Exogenous
		$LUCG=0.09$	Exogenous
		$GHG_{FG} = -28$	Exogenous
		$LUCM = 0.31$	Exogenous
		$GHG_{FM}=10.7$	Exogenous
		$LUCS=0.18$	Exogenous
		$GHG_{FS} = -22$	Exogenous
		$LUCSh = 0.08$	Exogenous
		$GHG_{FSh} = -10$	Exogenous
		$LUCW = 0.01$	Exogenous
		$GHG_{FW} = -19$	Exogenous
		$LUCB= 0.01$	Exogenous
$GHG_{FB}= 0$	Exogenous		
5	GHG by biodiesel production and supply chain transport	Equation 3-85 $GHG_{BdPr\&Transp} = GHG_{FBdPr\&Transp} \times BdPr1G$	Endogenous
		$GHG_{FBdPr\&Transp}=1.19$	Exogenous
6	GHG if Diesel 100% is used in Colombian transport sector	Equation 3-86 $GHG_{ifDiesel} = GHG_{FLCD} \times BdPr1G$	Endogenous
		$GHG_{FLCD}= 3.57$	Exogenous
7	GHG in life cycle of biodiesel	Equation 3-87 $GHG_{inLCBd} = GHG_{P\&POE} + GHG_{DLUC} + GHG_{ILUC} - GHG_{abs}$	Endogenous
		Equation 3-88 $\%GHG_{saving} = \frac{(GHG_{ifDiesel} - GHG_{inLCBd})}{GHG_{ifDiesel}} \times 100$	Endogenous

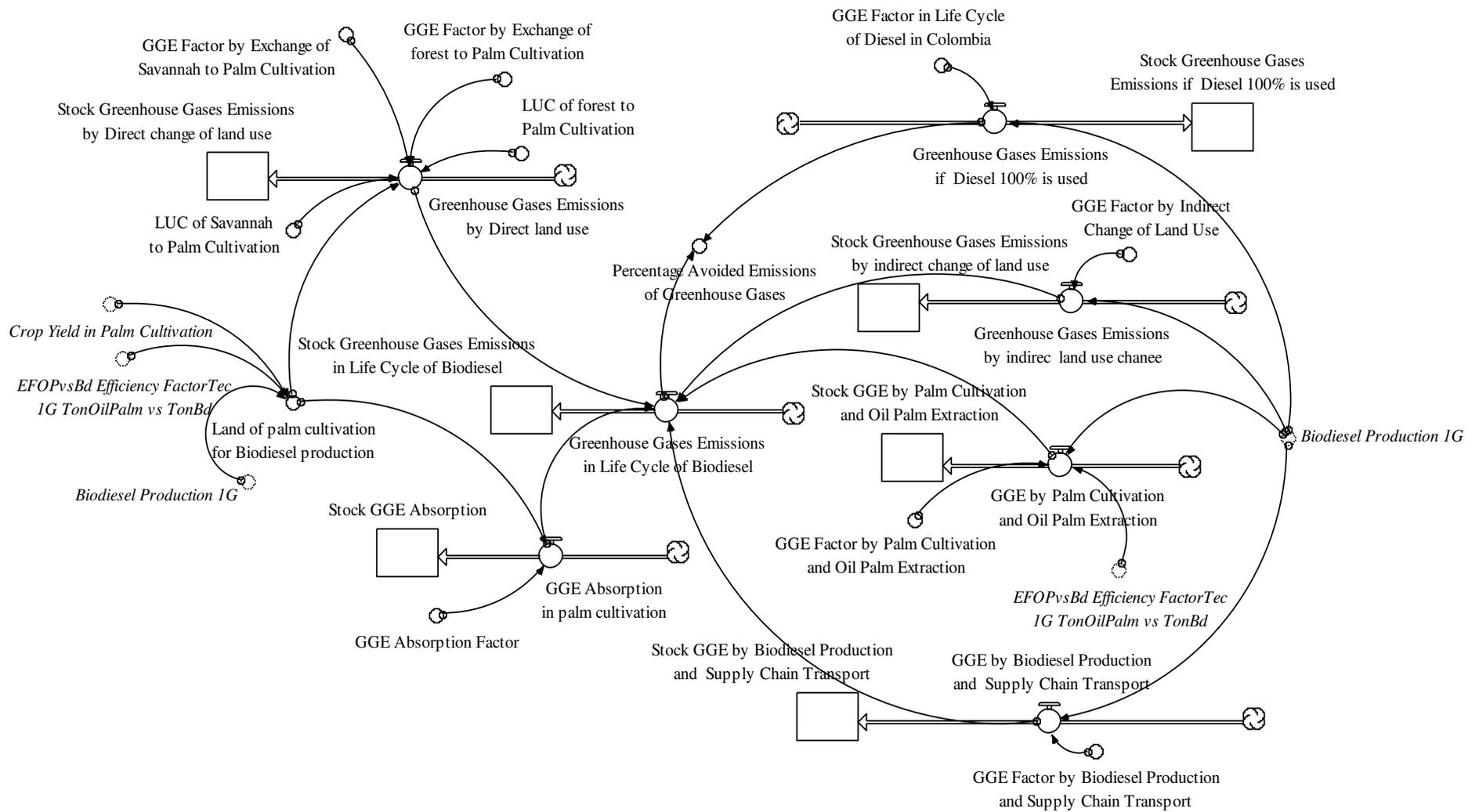


Figure 3-17 GHG emissions saving in life cycle of biodiesel sub-model

In GHG emissions saving in life cycle of biodiesel sub-model there are input indicators that come from of other sub-models. They are shown in Table 3-13.

Table 3-13 Input indicators used in GHG emission saving in life cycle of biodiesel sub-model

Indicator	Symbol	Sub-model of origin
Biodiesel production 1G	BdPr1G	Biodiesel production sub-model
Crop yield in palm cultivation	CrYieldPalm	Land and social sub-model
Efficiency Factor Technological biodiesel first generation tons palm oil per tons of biodiesel	EffFactTecPalmOilBd	Biodiesel production sub-model

- Pollutant emission that affect air quality as a consequence of the use of biodiesel - diesel blends as biofuel sub-model

This sub-model is composed of five S&F: carbon monoxide (CO) emissions, particulate matter (PM) emission, hydrocarbons (HC) emission, nitrogen oxides (NO_x) of biodiesel blended by diesel, and pollutant emission that affect air quality as a consequence of biodiesel: diesel blend as biofuel. Each S&F mentioned before to consider the percent change in emissions established by the Environmental Protection Agency (EPA 2002). In this study the percent change in emissions are called fraction driving of emissions change and it is a function of mix ratio biodiesel – diesel. The equations that describe each S&F are shown in Table 3-14, and the graphical S&F is presented in Figure 3-18. The equation constants are displayed in the Appendix 2 and the statistical issues of equation definitions are describe in the Appendix 3. The endogenous and exogenous indicators used in each equation are described in Table 3-1 and Table 3-2 respectively.

Table 3-14 Stock and flow equations by pollutant emission sub-model

#	S&F	Equation	Indicator
1	Carbon monoxide (CO) emissions	Equation 3-89 If time > 8 then [COEmissions = (FCODiesel × DiConsTransp) + FDCO × ((FCODiesel × DiConsTransp) – 1)] else [COEmissions = FCODiesel × DiConsTransp]	Endogenous
		Equation 3-90 FDCO = A1 – A2 × MxRtBdDi + A3 × MxRtBdDi ²	Endogenous
		FCODiesel = 0.017	Exogenous
		DiConsTransp refer to Equation 3-13	Endogenous
2	Particulate matter (PM) emission	Equation 3-91 If time > 8 then [PMEmissions = (FPMDiesel × DiConsTransp) + FDPm × ((FPMDiesel × DiConsTransp) – 1)] else [PMEmissions = FPMDiesel × DiConsTransp]	Endogenous
		FPMDiesel = 5.5E-07	Exogenous
		Equation 3-92 FDPm = A1 – A2 × MxRtBdDi + A3 × MxRtBdDi ²	Endogenous
3	Hydrocarbons (HC) emission	Equation 3-93 If time > 8 then [HCEmissions = (FHCDiesel × DiConsTransp) + FDHC × ((FHCDiesel × DiConsTransp) – 1)] else [HCEmissions = FHCDiesel × DiConsTransp]	Endogenous
		FHCDiesel = 1.8E-03	Exogenous
		Equation 3-94 FDHC = –A1 – A2 × MxRtBdDi + A3 × MxRtBdDi ²	Endogenous
4	Nitrogen oxides (NO _x)	Equation 3-95 If time > 8 then [NOxEmissions = (FNOxDiesel × DiConsTransp) + FDN0x × ((FNOxDiesel × DiConsTransp) – 1)] else [NOxEmissions = FNOxDiesel × DiConsTransp]	Endogenous
		Equation 3-96 FDN0x = A1 × MxRtBdDi	Endogenous
		FNOxDiesel = 6.3E-02	Exogenous

#	S&F	Equation	Indicator
5	Pollutant emission that affect air quality as a consequence of the use of biodiesel - diesel blends as biofuel	Equation 3-97 If time > 8 then [PEAirQBdD = COEmissions + PMEmissions + HCEmissions + NOxEmissions] else [PEAirQBdD = 0]	Endogenous
		Equation 3-98 $PEAirQifDiesel100\% = COEmissionsDi + PMEmissionsDi + HCEmissionsDi + NOxEmissionsDi$	Endogenous
		Equation 3-99 $COEmissionsDi = FCODiesel \times DiConsTransp$	Endogenous
		Equation 3-100 $PM EmissionsDi = FPMDiesel \times DiConsTransp$	Endogenous
		Equation 3-101 $HCEmissionsDi = FHCDiesel \times DiConsTransp$	Endogenous
		Equation 3-102 $NOxEmissionsDi = FNOxDiesel \times DiConsTransp$	Endogenous

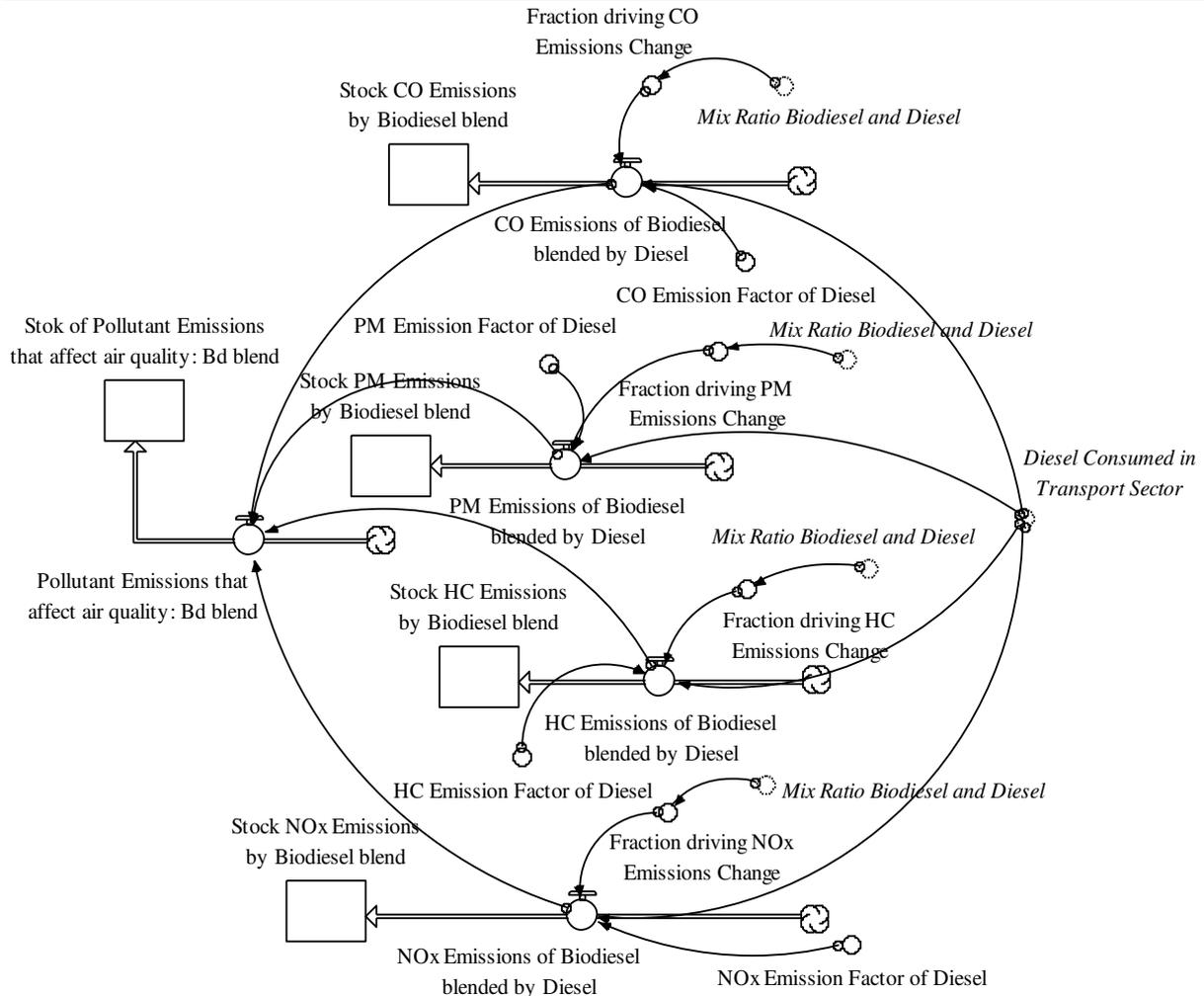


Figure 3-18 Pollutant emission that affect air quality: Biodiesel blended by diesel sub-model

In this sub-model there are input indicators that come from of other sub-models, as Table 3-15 shows.

Table 3-15 Inputs indicators used in pollutant emission that affect air quality: biodiesel blended by diesel sub-model

Indicator	Symbol	Sub-model of origin
Mix ratio biodiesel - diesel	MxRtBdDi	Biodiesel production
Diesel consumed in transport sector	DiConsTransp	

3.4.5 Testing and analysis

Once the model was defined and its boundaries were established, the following step in the SD methodology is the validation. To validate a SD model three validation criterion were defined.

The first criterion is the correspondence between structures, the second is the correspondence between behaviors and the third is the correspondence between phenomena.

To validate the correspondence between structures, the integral causal diagram in Figure 3-8 was validated through expert consultation. It was validated by personal interviews with five Colombian experts of biodiesel production, who confirmed the relationships established. The correspondence between behaviors and phenomena are measured by the Mean Absolute Percentage Error (MAPE), which calculates the accuracy of the model prediction, defining a MAPE up to 30% as valid (Barlas 1989; Barlas 1994). To calculate MAPE, the model was used to simulate behaviors and phenomena; the values generated by the model were compared against the collected historical values between 1999 and 2013. The MAPEs of some indicators (the most important for the SD model) are presented in Table 3-16, where it can be noted that they are lower than 30%. Then, according to this validation criterion the causal relationships and equations satisfied validation condition, and the SD model could represent adequately the behavior of the sustainability assessment of biodiesel production in Colombia (Appendix 3 describes the statistics issues).

Table 3-16 Dynamic model validation using MAPE

Indicator	MAPE 1999-2013
Agricultural land	10.04%
Forest and ecosystems lands	2.85%
Land for palm cultivation	2.62%
Better Quality Employment in Palm Cultivation	4.70%
Biodiesel production 1G	15.04%
Biodiesel production capacity 1G	17.45%
Crop yield in palm cultivation	5.31%
Detriment of Quality Employment in Palm Cultivation	4.90%
Index of energy diversity of Colombia	13%
Land Concentration Index: GINI	0.20%
Livestock land	1.34%
NER – Net energy ratio	5.30%
Palm oil production	5.68%
Poor population	6.40%
Population displaced by violence	21.70%
Profit Biodiesel Production 1G	14%
Biodiesel price	6.67%
Biodiesel production costs	6.80%
Diesel consumed in transport sector	7.90%
Diesel price	4.07%
Fraction driving CO Emissions Change	0.20%
Fraction driving PM Emissions Change	0.10%
Fraction driving HC Emissions Change	0.30%
Fraction driving NOx Emissions Change	0.20%
Mix ration biodiesel - diesel	0.90%
Palm oil price	16.02%
Others Biodiesel Production Costs Dependent of Biodiesel Production	3.50%
Percentage GHG saving in life cycle of biodiesel production	4.02%

Conclusions

Using system dynamics methodology, a model to assess the sustainability of biodiesel production in Colombia was established and validated. It was based on the sustainability assessment framework presented in Chapter 2, which includes principles, criteria and indicators for the five sustainability dimensions defined in this work.

SD methodology enables the articulation of the problem and its conceptualization through causal loop diagrams. These diagrams describe the complex relationships between dimensions and indicators, as well as the polarity of the effects and the feedback structures of biodiesel production, integrating the economic, social, environmental, political and technological indicators. The SD model is defined by five sub-models: biodiesel production, land and social, water, net energy ratio, greenhouse gas saving in the life cycle of biodiesel and pollutant emissions that affect air quality: Biodiesel blended by diesel. The validation of the model through MAPE test confirms the correspondence between structures and phenomena.

Chapter 4: System dynamic model of sustainability assessment of biodiesel production in Colombian context - Results

Introduction

Conduct biodiesel production on sustainable principles is fundamental to ensuring an appropriate local development (Silalertruksa and Gheewala 2012). The objective of the definition and design of the system dynamic (SD) model described in Chapter 3 is to develop a tool that allows the decision maker to predict the behavior of the biodiesel production system in Colombian context considering different conditions for its development and, finally, to establish which of these conditions will generate biodiesel production accomplishing sustainable principles. In this chapter, the SD model presented in Chapter 3 and implemented in software Stella[®], is going to be used to simulate the biodiesel production in Colombian context considering baseline conditions.

The baseline considers that current conditions for biodiesel production, represented by the exogenous indicators, will be the same during all the period under analysis (from 2014 to 2030). As a consequence, the trends and functions between 1999 and 2013 will be the same up to 2030. After, some exogenous indicators of the baseline scenario will be modified in order to generate a sensibility analysis to define several fundamental conditions for the sustainable biodiesel production in the Colombian context. Once the sensibility analyses have been conducted, the conditions that promote or discourage biodiesel production could be identified. Consequently, optimistic and pessimistic scenarios are proposed.

The results of the analysis of the scenarios can help institutions, decision-makers and other agents related to establish the conditions to be carried out to promote a sustainable biodiesel production, in order to make more robust decisions about the management of this system.

4.1 Baseline

The baseline scenario considers that the current status of Colombian biodiesel production will be constant during all the period under analysis (2014 to 2030). This scenario takes into account

that the endogenous and exogenous indicators presented in Chapter 3, Table 3-1 and Table 3-2, which represents the dynamics of the Colombian biodiesel system between 1999 and 2013, will represent the behavior from 2014 to 2030. The specification to simulate the system is: Length of simulation from 1999 (time 0) to 2030 (time 31), unit of time years, and Euler as integration method. Simulation results classified according to each sustainability dimension are described following.

4.1.1 Economic dimension

The economic indicators palm oil production, biodiesel production capacity and biodiesel production predicted by the SD model are shown in Figure 4-1. They follow the same trend of diesel consumed in the transport sector, which will increase during the period of analysis. This trend is expected because biodiesel is blended with diesel and therefore if the diesel market grows biodiesel market too. In the same way, palm oil production will increase from 488,000 t in 1999 to 850,000 t in 2030, a growth of 42% in thirty years. At the same time, biodiesel production will increase from 520,000 t in 2013 to 988,000 t in 2030, a growth of 52% during the period of analysis. Biodiesel production capacity predicted will increase and will be higher than biodiesel production up to 2017. Then, between 2018 and 2030 they will be equal. As a consequence, production capacity will limit biodiesel production as can be seen in Figure 4-1.

Estimated biodiesel consumption in transport sector will increase to 450,000 t in 2018 until 3,000,000 t in 2030, considering that the increment in blend ratio biodiesel-diesel, predicted 0.05 in 2008 and 0.26 in 2030. On the other hand, biodiesel production in 2018 will be 830,000 t and 988,000 t in 2030 (Figure 4-1). This difference will lead to an unsatisfied demand of biodiesel in Colombia. The principal limitation for the biodiesel production increase is the biodiesel production capacity and high biodiesel production costs (Figure 4-2), which are greatly influenced by governmental control and support.

Figure 4-2 shows the prediction for other economic indicators. For example, palm oil price, oil price and diesel price predicted by the model will have a similar behaviour and a continuous increment between 2014 and 2030, although the rate of change during this period will be higher than between 2008 and 2013. As palm oil price will increase and the production costs of biodiesel depend on it in a percentage close to 70%, the predicted behaviour of biodiesel production costs is similar to palm oil price. Biodiesel price will increase at the same rate of the previously mentioned variable.

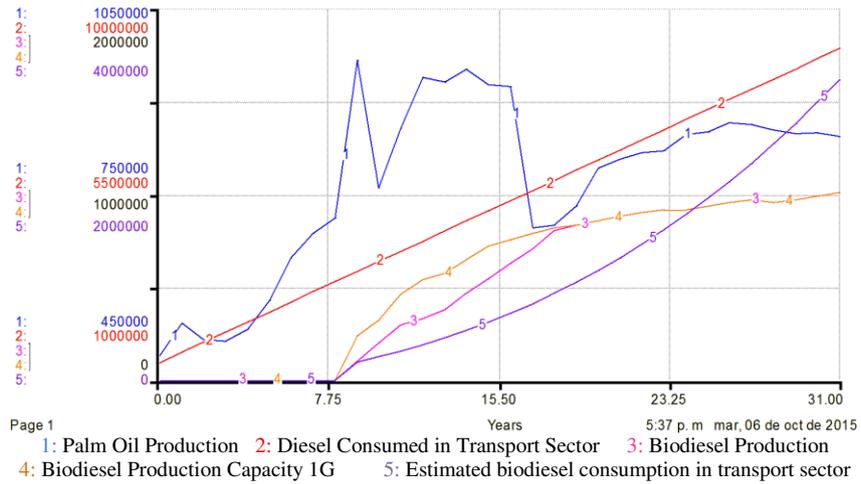


Figure 4-1 Graphical output of economic indicators of model in baseline

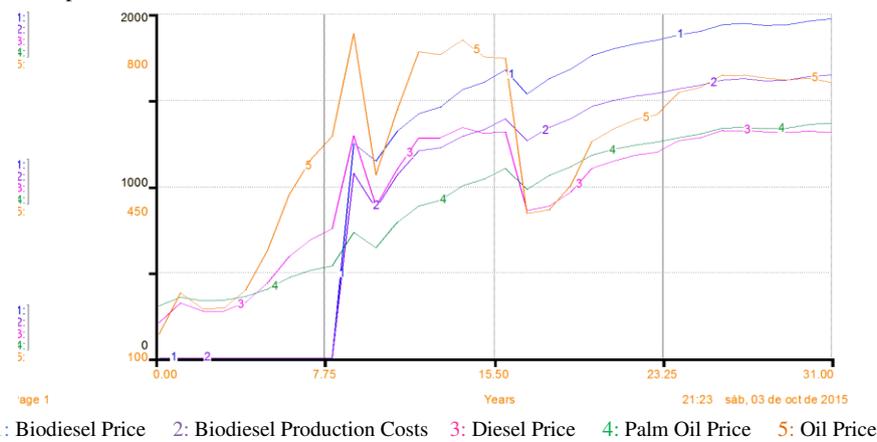


Figure 4-2 Graphical output of economic indicators of model in baseline

Colombian government supports biodiesel sector through tax exceptions and subsidies; this led to an increase of costs linked to biodiesel policy as shown in Figure 4-3. Biodiesel profit margin will remain around the same value over the period of analysis, showing fluctuations produced by the biodiesel price change. This reflects the effect of Colombian government control on the biodiesel and diesel market, to ensure biodiesel production profitability.

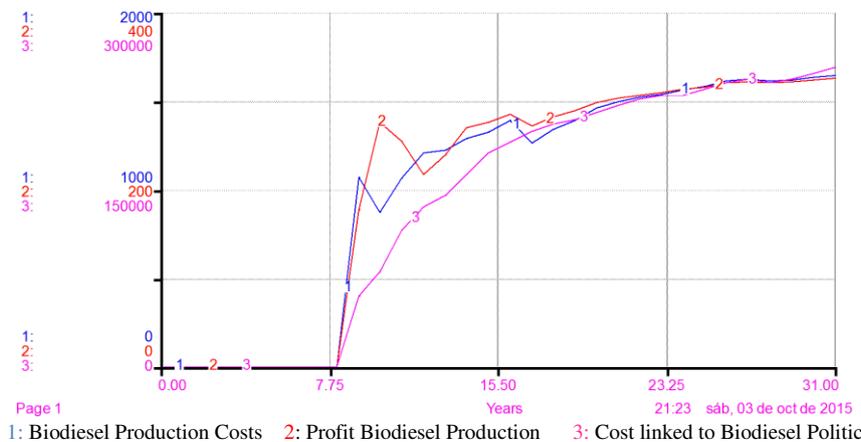


Figure 4-3 Graphical output of economic indicators of model in baseline

4.1.2 Social dimension

The social indicators population displaced by violence, and poor population predicted by the SD model are shown in Figure 4-4, they follow similar decrease. In the SD model both indicators are inversely proportional to lands for oil palm cultivation. Then if oil palm cultivation increases, population displaced and poor population will decrease. This behavior can be explained because increments in oil palm cultivation, increment rural employment. Then the former will contribute to local economies (Fedesarrollo 2009). In order to have a better understanding of this phenomenon, it will be necessary to integrate other indicators to explain that poverty and violence displaced diminish.

Figure 4-4 shows the prediction for other social indicators. Concerning land concentration index (Gini) predicted by the SD model, this index varies depending on the changes in livestock lands, oil palm cultivation, oil price, and biodiesel production. Gini index remains around of 0.76 to 0.77 over the period of analysis, which indicates a high concentration and inequality distribution of land ownership. A high concentration of land is linked to poverty and violence condition in Colombian context (Castiblanco, Etter, and Ramirez 2015). Regarding the food security indicator predicted by the SD model (hectare of agricultural lands per hectare of palm-oil cultivation), it shows an important reduction, from 14.5 in 1999 to 0.3 in 2030 (Figure 4-4), especially because agricultural lands diminish too (Figure 4-5). Agricultural lands decrease in inverse proportion to palm-oil cultivation and livestock lands. However, the effect of the latter is greater than the influence of the former on agricultural land reduction. Furthermore, social research identified that agricultural lands diminution could intensify poverty and violence conditions in region influenced by oil palm cultivation (Mingorance 2006; FIAN 2009; Alvarez R 2012).

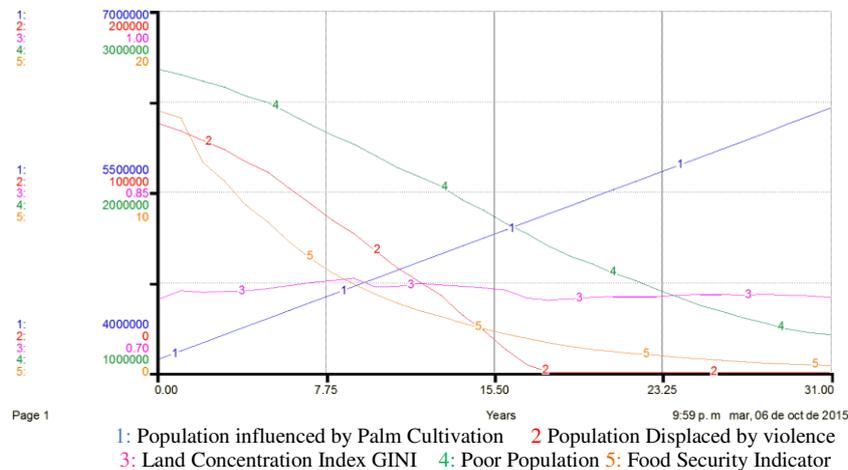
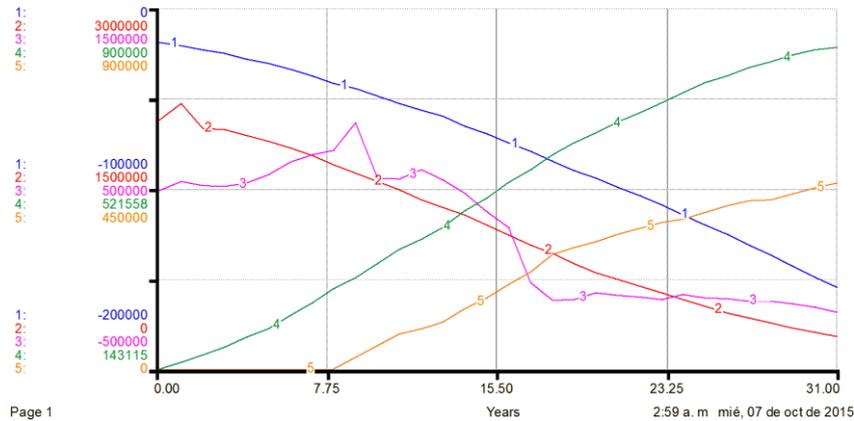


Figure 4-4 Graphical output of social indicators of model in baseline

In Colombia, palm oil is used to biodiesel production and other uses, such as foods and oleochemical products. Other uses palm-oil sales will decrease from 2008 to 2030, as shown in Figure 4-5. This trend is expected because more palm oil will be used for biodiesel production. About 43% of oil palm cultivation will be used for biodiesel production in 2030. Concerning to quality of employment in palm-oil cultivation, this indicator will diminished, but this will not influence the amount of lands for palm-oil cultivation as shown in Figure 4-5. In long-time, increment in oil palm cultivation will decrease the quality of employment.

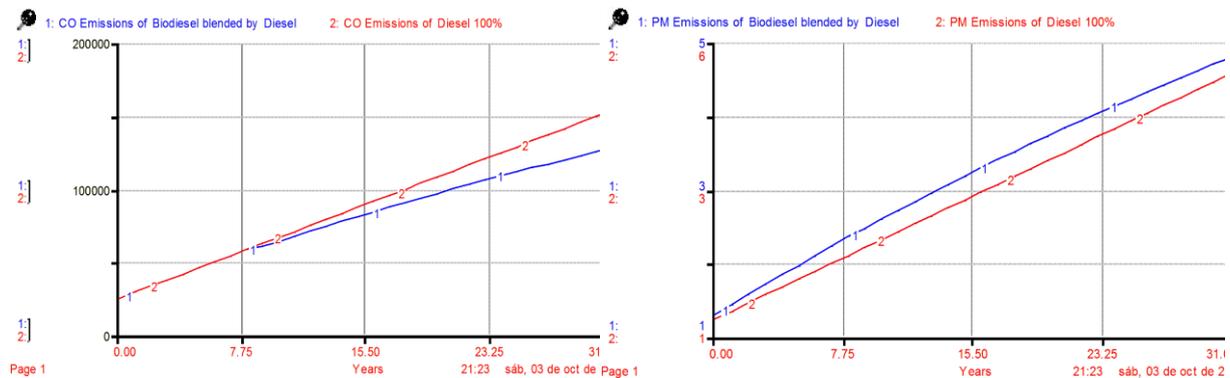


Page 1
 1: Quality of employment in Palm Cultivation 2: Agricultural Land 3: Palm Oil Sales to other uses
 4: Land for Palm Cultivation 5: Land of Palm Cultivation for Biodiesel Production

Figure 4-5 Graphical output of social indicators of model in baseline

4.1.3 Environmental dimension

Environmental indicators related to pollutant emissions that affect air quality show a slight decrease in the period of analysis as a consequence of the use of blends biodiesel – diesel as fuel (Figure 4-6). This trend is expected because pollutant emissions are influenced by the blend ratio. It is observed that if the blend ratio biodiesel – diesel increases, HC, CO and PM emissions will diminish, but NOx emission will increment. The total reduction of pollutant emissions predicted in 2030 is 2%, equivalent to 14,075 t, which is a positive but not significant impact on air quality.



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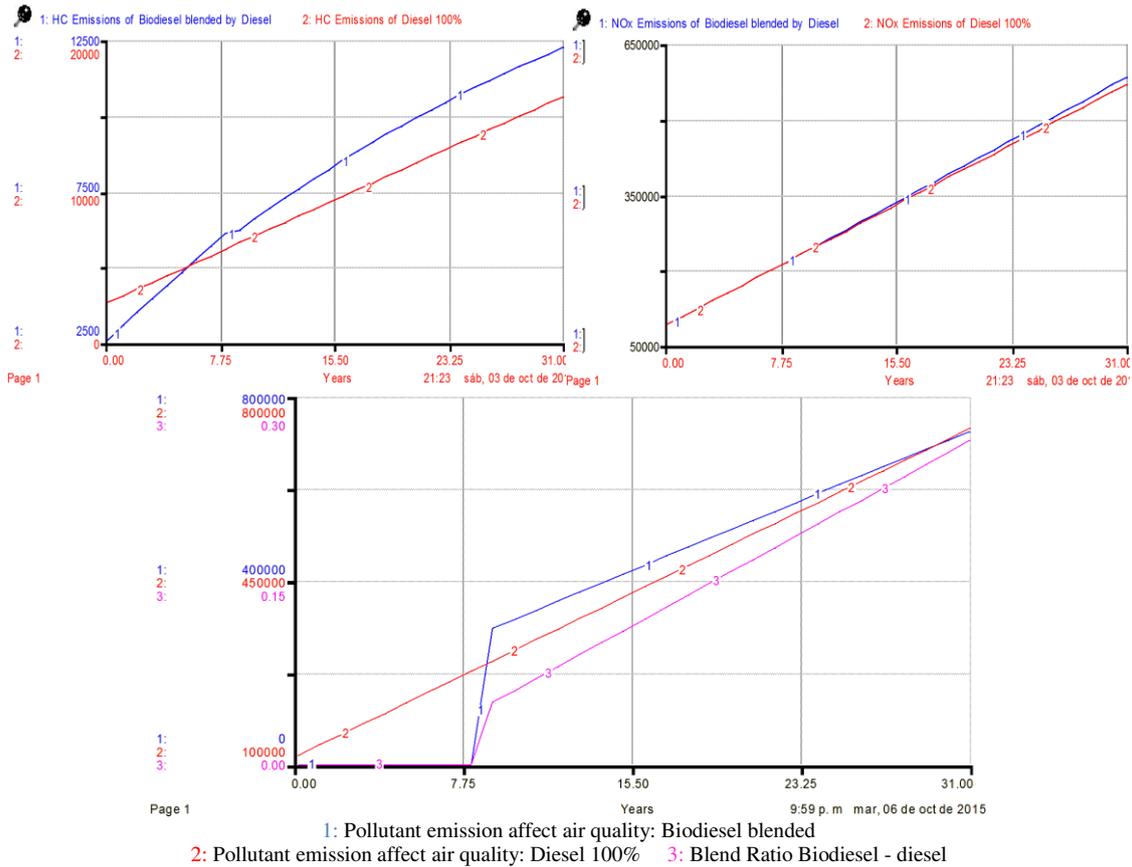


Figure 4-6 Graphical output of environmental indicators of model in baseline

GHG emissions in the biodiesel production life cycle come from many sources as shown in Figure 4-7 and Figure 4-8. GHG emissions by direct land use change are the largest contributor of GHG in the life cycle, particularly in this case, due to land use change of forest and ecosystem lands to palm-oil cultivation.

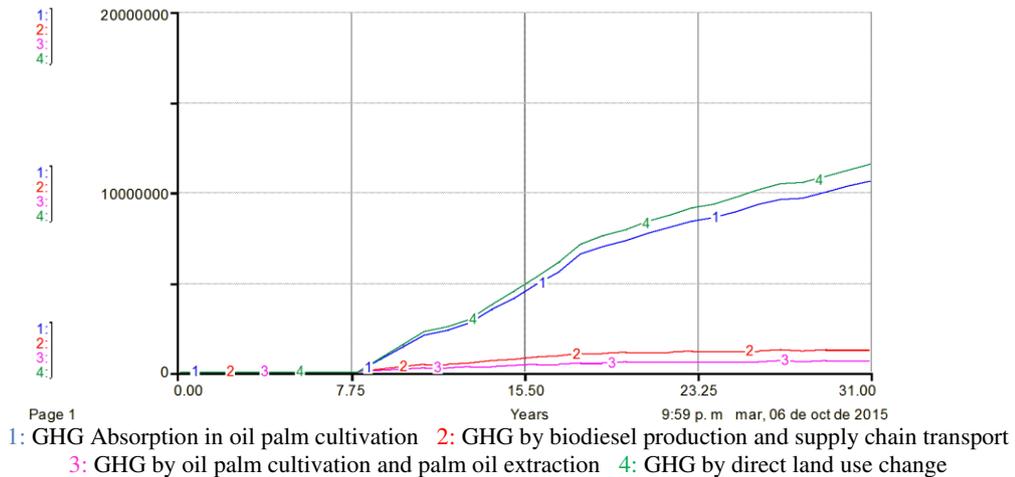
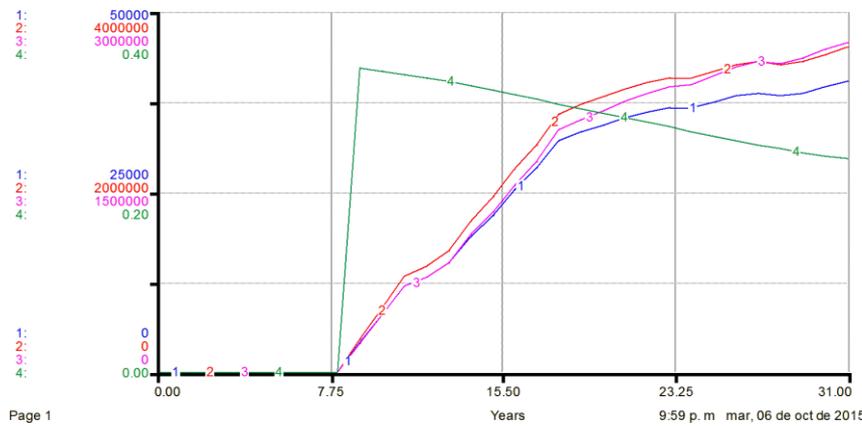


Figure 4-7 Graphical output of environmental indicators of model in baseline scenario

Based on the indicator analysed in GHG emission sub-model, it is identified that if crop yield in palm cultivation will decrease, and the efficiency factor (tons of palm oil consumed per tons biodiesel produced) remains constant, the fraction of GHG emission saving predicted by SD

model will decrease from 0.34 in 2008 to 0.24 in 2030 (Figure 4-8). If the fraction of GHG emission saving is lower than 0.4, biodiesel produced in Colombia will be less competitive in the international market (RFS2 2010).

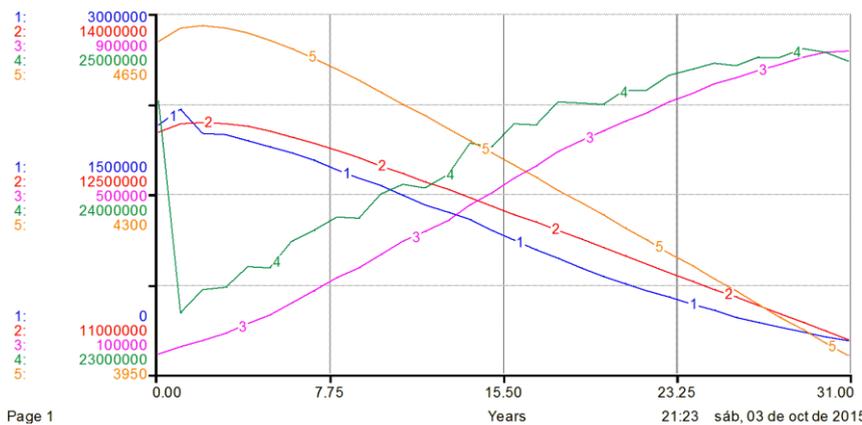


1: GHG emissions by indirect land use change 2: GHG emissions if Diesel 100% is used

3: GHG emissions in life cycle of biodiesel 4: Fraction of GHG emission saving by biodiesel-diesel blended

Figure 4-8 Graphical output of environmental indicators of model in baseline scenario

Figure 4-9 shows the prediction for the land use indicator. Regarding the prediction for agricultural, forest and ecosystem lands, they will have a similar behaviour and a continuous diminution between 1999 and 2030. On the other hand, livestock and oil palm lands will have increments in the same period. In the case of agricultural lands, an important change is observed from 2,000,000 ha in 1999 to 260,000 ha in 2030, a reduction of 87% in thirty years. In this SD model the increment in palm-oil cultivation and livestock lands partially explains this behaviour, but it is important conduct further research to clarify others factors that influence it.



1: Agricultural Land 2: Forest and Ecosystems lands 3: Land for Palm Cultivation, 4: Livestock Land 5: Biodiversity Indicator

Figure 4-9 Graphical output of environmental indicators of model in baseline scenario

In Figure 4-10 is observed that agrochemicals applied and soil loss in oil palm cultivation will increment in the period of analysis by the SD model. Crop yield in palm cultivation will decrease from 4.1 in 1999 to 2.2 in 2030. Reduction of crop yield will influence the increment of demand for new lands for oil palm cultivation to satisfy palm oil demand.

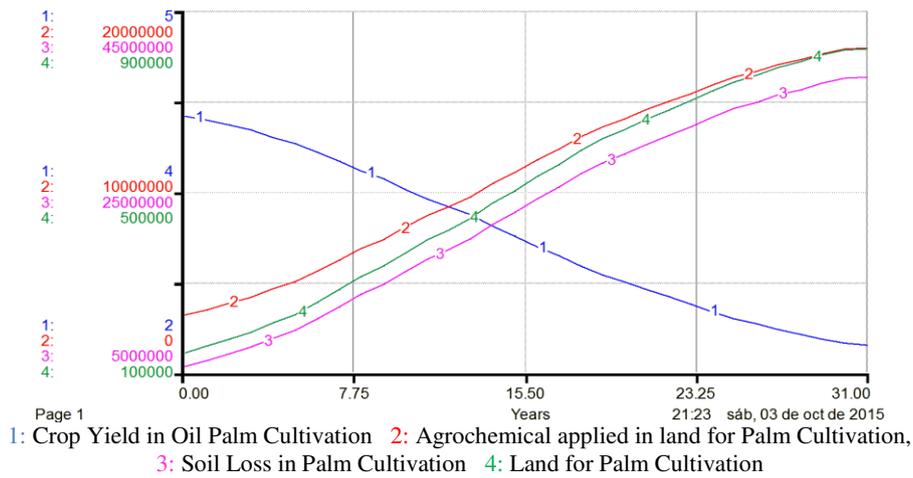


Figure 4-10 Graphical output of environmental indicators in baseline scenario

The prediction of water demanded by anthropic activities in the region influenced by oil palm cultivation and biodiesel production, as shown in Figure 4-11 and Figure 4-12. Water demanded predicted by livestock lands is the largest contributor of total demand. Concerning to water scarcity index predicted has an increment of 1.81×10^{-8} in 1999 to 1.88×10^{-8} in 2030. Scarcity index prediction is limited by the lack of annual data about water supply. Thus, in the SD model water supply is considered constant in the period of analysis, as shown in Figure 4-12.

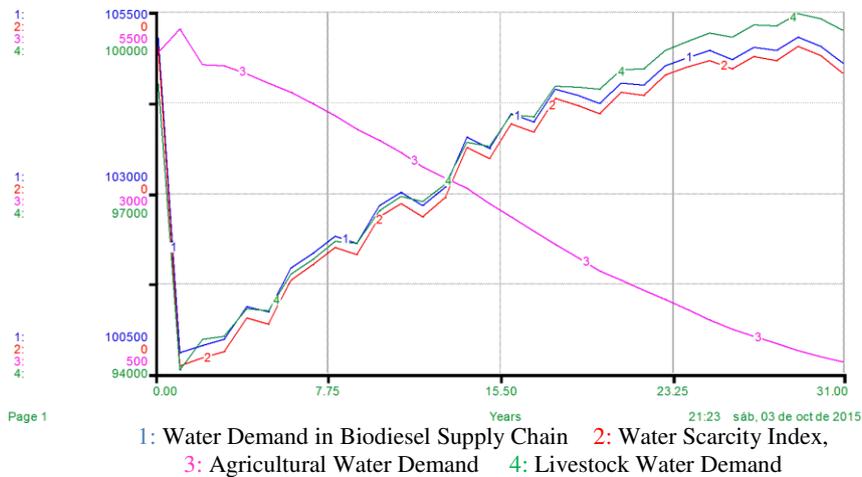
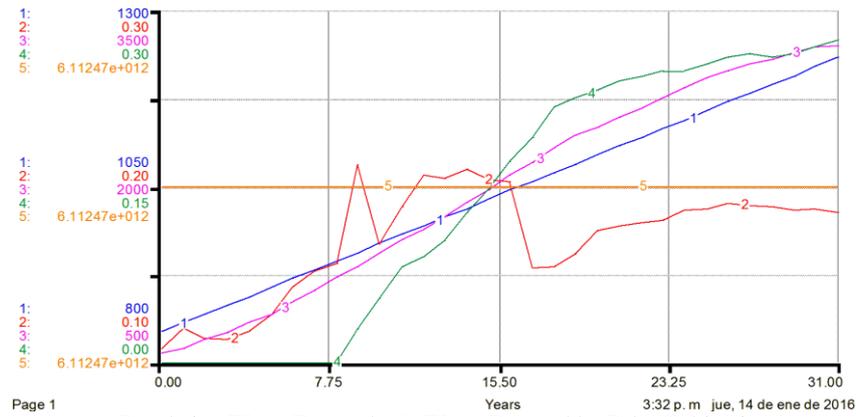


Figure 4-11 Graphical output of environmental indicators of model in baseline scenario



1: Population Water Demand 2: Water Demand by Palm Cultivation, 3: Water Demanded by Palm Oil Extraction 4: Water Demand by Biodiesel Production 5: Water Supply

Figure 4-12 Graphical output of environmental indicators of model in baseline scenario

Energy inputs in biodiesel supply chain are shown in Figure 4-13. The stages of the process that contribute to energy inputs are: oil palm extraction, co-product treatments (kernel oil, kernel cake and glycerol), transesterification, oil palm cultivation and transportation. In the SD model, due they are considered constant in the period of analysis because of the scarcity of data.

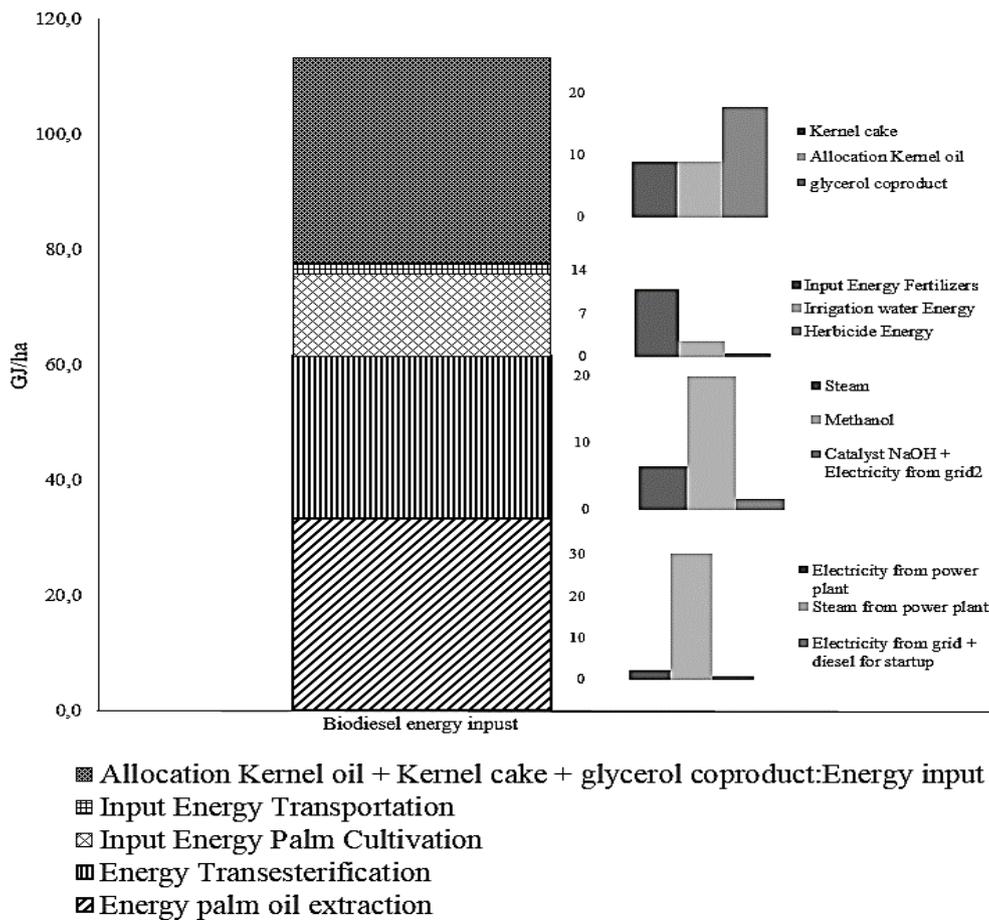


Figure 4-13 Graphical output of environmental indicators of model in baseline

Figure 4-14 shows energy outputs, which are biodiesel energy, glycerol energy, palm kernel oil energy, palm kernel cake energy and soaps energy. Net energy ratio (NER) predicted by the SD

model, diminishes from 4.9 in 2008 to 2.9 in 2030. In the SD model the principal indicator that influences NER is the crop yield in palm cultivation. Thus, the energy output follows the same trend that variable, which will decrease during period of analysis as shown in Figure 4-18.

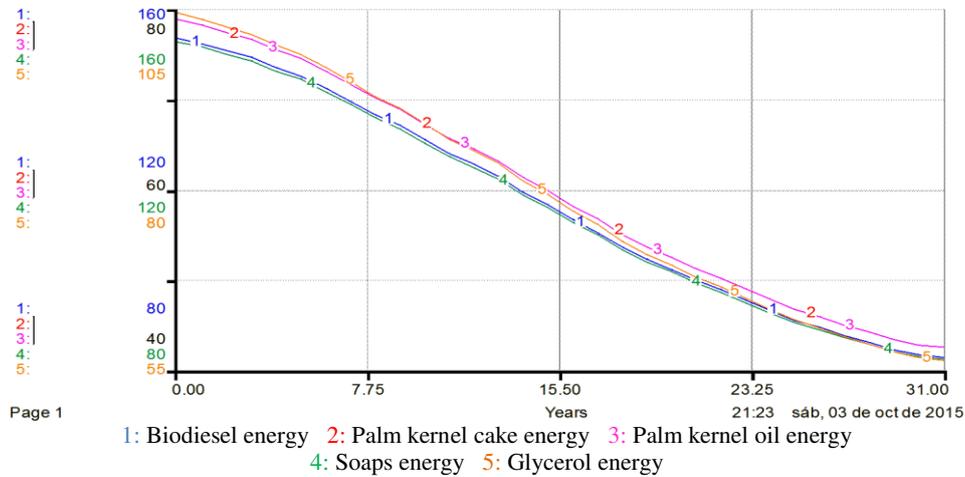


Figure 4-14 Graphical output of environmental indicators of model in baseline

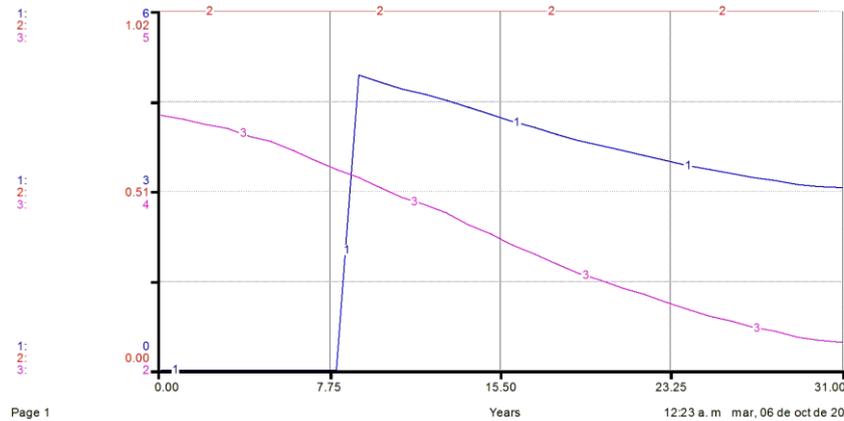


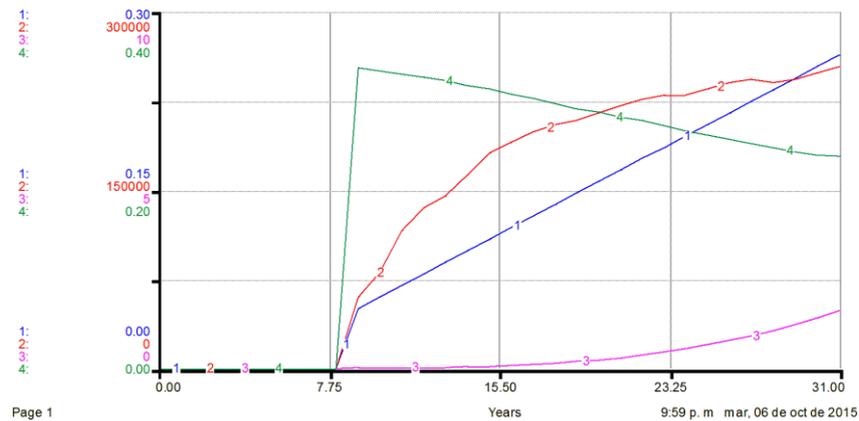
Figure 4-15 Graphical output of environmental indicators of model in baseline

4.1.4 Political dimension

As mentioned previously, Colombian government supports biodiesel sector through tax exceptions and subsidies, which in SD model are predicted through costs linked to biodiesel policy. Figure 4-16 shows that these costs increase in the period of analysis. This condition promotes the increment in blend ratio biodiesel-diesel, predicted 0.05 in 2008 and 0.26 in 2030. Furthermore, in the SD model costs linked to biodiesel policy will increase, as well as biodiesel production capacity. Taking into account that the predicted biodiesel profitability is low and biodiesel production costs will increase, the investment in biodiesel capacity is discouraged, so government support is necessary to promote growths in biodiesel production capacity. The

political indicator about energy diversity index predicted by the SD model has a similar trend than the biodiesel production.

It should be noted that if biodiesel costs increase, biodiesel profitability, net energy ratio, and the fraction of GHG emissions saving in the life cycle of biodiesel diminish. So, it is very important to establish what conditions justify the Colombian government support to the biodiesel sector.



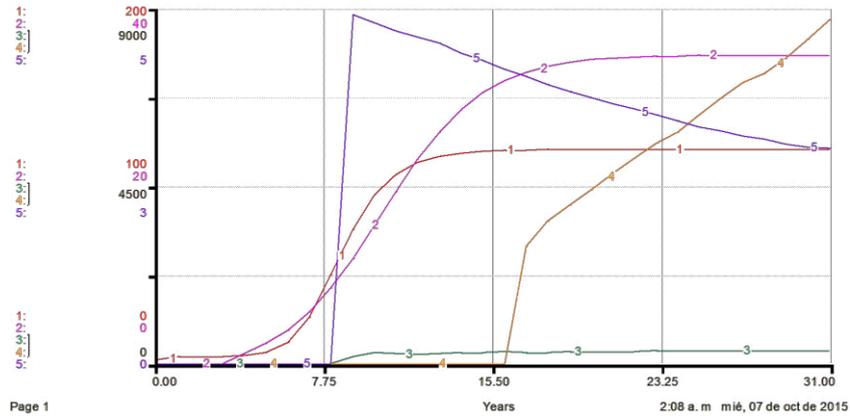
1: Mix Ratio Biodiesel and Diesel, 2: Cost linked to Biodiesel Politic,
3: Index of Energy diversity of Colombia, 4: Percentage Avoided Emissions of Greenhouse Gases

Figure 4-16 Graphical output of politics indicators of model in baseline

4.1.5 Technological dimension

The technological indicators shown in Figure 4-17 and Figure 4-18 are related to the maturity degree of first, second and third generation technologies through the evolution of the number of patents and articles in scientific journals about these technologies, the national and international biodiesel production, the technological efficiency factor (palm oil consumed per biodiesel produced), the net energy ratio, the biodiesel profitability and the profit by valorization of glycerol through PDO.

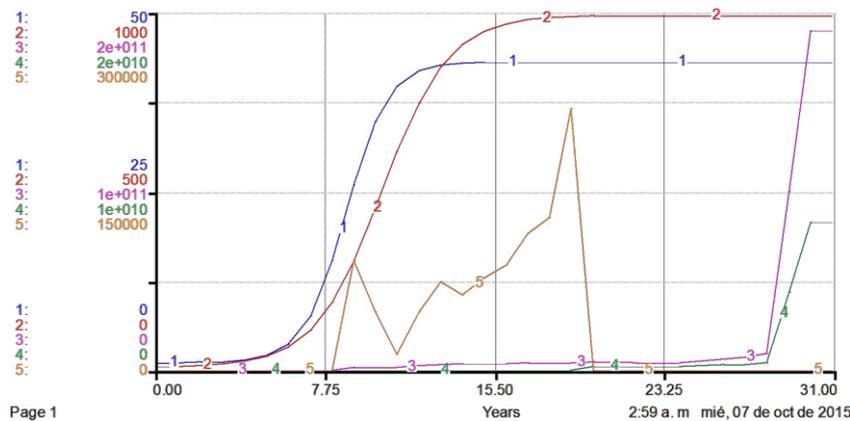
Patents and articles predicted by the SD model (published in scientific journals and data bases) about biodiesel production of first generation are shown in Figure 4-17. They follow the same trend of patents and articles about biodiesel production of second and third generation shown in Figure 4-18. These trends can be linked to the technological maturity in biodiesel production. As a consequence, the SD model predicts that valorization of glycerol is possible from 2016. The profit by this valorization can be added to biodiesel profitability.



1: Articles in Journal scientific about Biodiesel production 1G 2: Patents about Biodiesel production 1G
 3: Profit of biodiesel production 4: Profit of valorization glycerol through PDO 5: Net energy ratio

Figure 4-17 Graphical output of technological indicators of model in baseline

Another possible result according to the prediction considering technological maturity is Colombia will produce biodiesel of second and third generation. The SD model considers that if unsatisfied biodiesel demand and international biodiesel production increase, the conditions will be given for the ignition of Colombian second and third generation biodiesel production, as shown in Figure 4-18. The SD model predicts that unsatisfied biodiesel demand will be high in 2022. Thus, biodiesel production of second and third generation in Colombia will start around this year. This production will be added to biodiesel production of first generation. Hence, with the total biodiesel production it will be possible to satisfy biodiesel demand in the period 2022 to 2030, as is shown in Figure 4-18.



1: Patents about Biodiesel production 2G and 3G 2: Articles in journal scientific about Biodiesel production 2G and 3G
 3: International Production of Biodiesel 2G and 3G 4: Colombian biodiesel production of 2G and 3G
 5: Unsatisfied demand of biodiesel in transport sector

Figure 4-18 Graphical output of technological indicators of model in baseline scenario

4.2 Sensitivity analysis

The sensitivity analysis enables to know how the SD model is sensitive to different assumptions. The STELLA® software does provide a platform for carrying out sensitivity simulations (Tao and Li 2007). The simulations performed in the sensitivity analysis predict future values of selected output indicators (endogenous) through a five-replicated simulations based on input indicators (exogenous). Simulation results are evaluated under a number of “what if”. Each selected input indicator has an incremental variation in the established range presented in Table 4.1. Each input indicator is simulated to know its effect on the six output indicators. The input indicators are selected because they are linked to exogenous indicators that are possible to be influenced by Colombian policy and governmental decisions.

Table 4-1 Input and output indicators in sensitive analyse

Input indicators (exogenous)	Units	Range	Output indicators (endogenous)
Oil price	USD/t	[150 - 850]	1 Biodiesel production first generation (1G)
Diesel vehicles	Dimensionless	[605,000 – 2,300,000]	2 Palm oil production
Factor of direct contrasts employees in palm cultivation	Dimensionless	[0.25 – 0.85]	3 Profit biodiesel production first generation
Costs linked to biodiesel politics	USD	[100 – 260,000]	4 Quality of employment in palm cultivation
Factor of agrochemicals applied in land for palm cultivation	t agrochemical / ha	[11 – 22]	5 Food security indicator (agricultural lands per land for palm cultivation)
Mix ratio biodiesel-diesel	Dimensionless (v/v)	[0.08 – 0.35]	6 Percentage GHG emissions saving compared with diesel petrochemical used
Efficiency factor technological biodiesel first generation tons palm oil per tons of biodiesel	Dimensionless	[0.9 – 1.04]	7 Net energy ratio
Factor of land use change of forest lands to oil palm cultivation	Dimensionless	[0 – 0.23]	8 Water scarcity index
			9 Pollutant that affect air quality by Biodiesel-diesel blended in transport sector

4.2.1 Oil price

Figure 4-19 provides incremental ranges for the effect of the oil price on six output indicators (endogenous). The results indicate that palm oil production and first generation biodiesel production profitability are sensitive to oil price. The reason is that if oil price increases, palm oil and biodiesel prices will increase because Colombian government must ensure a profit for biodiesel producers. If biodiesel price increase biodiesel profitability will increase too. If palm oil price increase, palm oil producers will lead to increment in palm-oil production. The other output indicators are not sensitive to oil price increment.

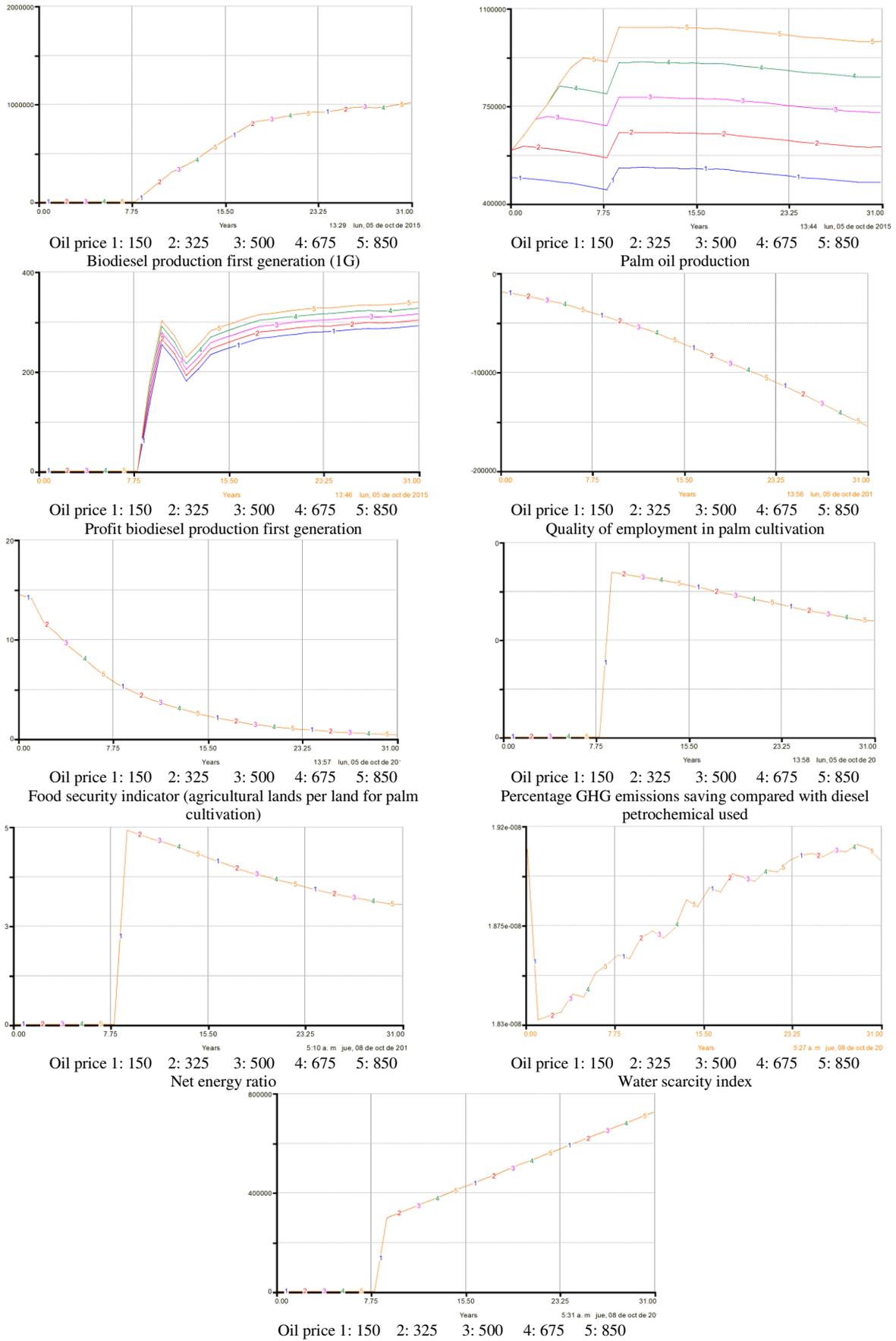
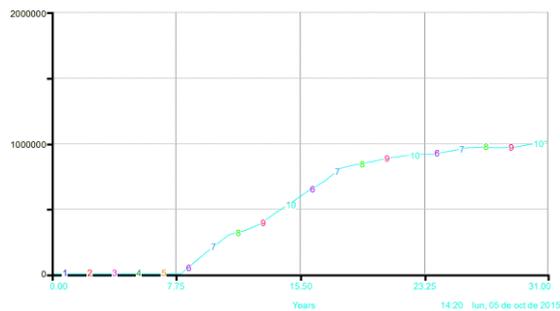


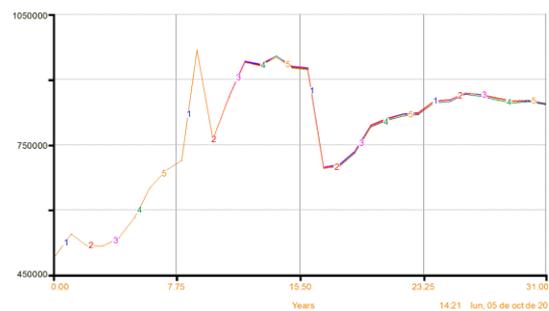
Figure 4-19 Sensitivity analyse of Oil price on the output indicators

4.2.2 Diesel powered vehicles

Figure 4-20 provides incremental ranges for the effect of the number of diesel powered vehicles on six output indicators (endogenous). Results indicate that if the number of diesel powered vehicles increase, the diesel consumption by the transport sector and the biodiesel demand will increase. Moreover, the output indicators are not always sensitive to an increase in biodiesel demand. This behavior is due to the fact that biodiesel production is not influenced by biodiesel demand in Colombia.

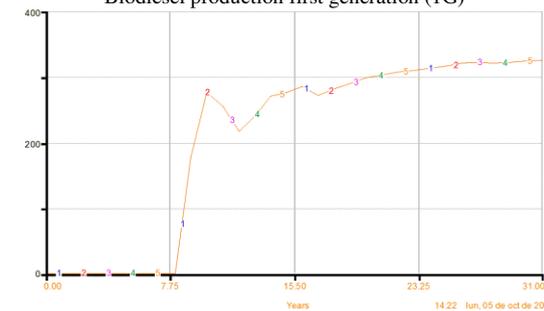


Number of diesel powered vehicles 1: 500E3 2:1.163 3: 1.8E6 4: 2.4E6 5: 3.0E6

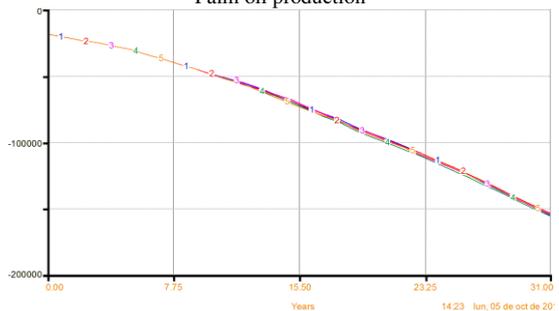


Biodiesel production first generation (1G)

Number of diesel powered vehicles 1: 500E3 2:1.163 3: 1.8E6 4: 2.4E6 5: 3.0E6

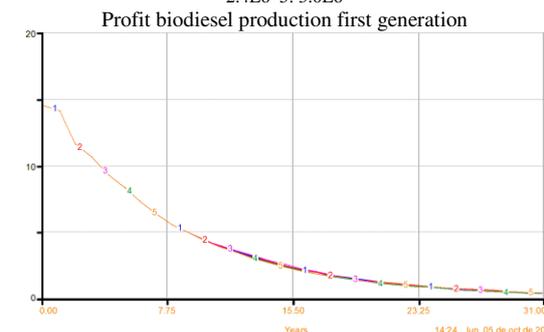


Palm oil production

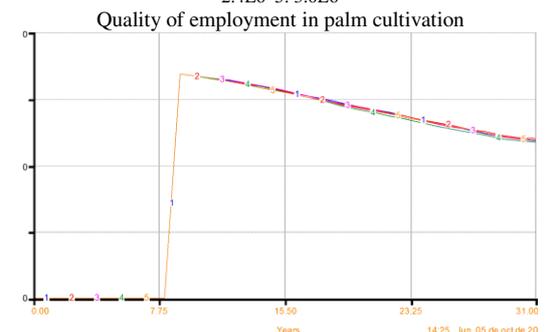


Number of diesel powered vehicles 1: 500E3 2:1.163 3: 1.8E6 4: 2.4E6 5: 3.0E6

Number of diesel powered vehicles 1: 500E3 2:1.163 3: 1.8E6 4: 2.4E6 5: 3.0E6



Profit biodiesel production first generation



Number of diesel powered vehicles 1: 500E3 2:1.163 3: 1.8E6 4: 2.4E6 5: 3.0E6

Number of diesel powered vehicles 1: 500E3 2:1.163 3: 1.8E6 4: 2.4E6 5: 3.0E6

Food security indicator (agricultural lands per land for palm cultivation)

Percentage GHG emissions saving compared with diesel petrochemical used

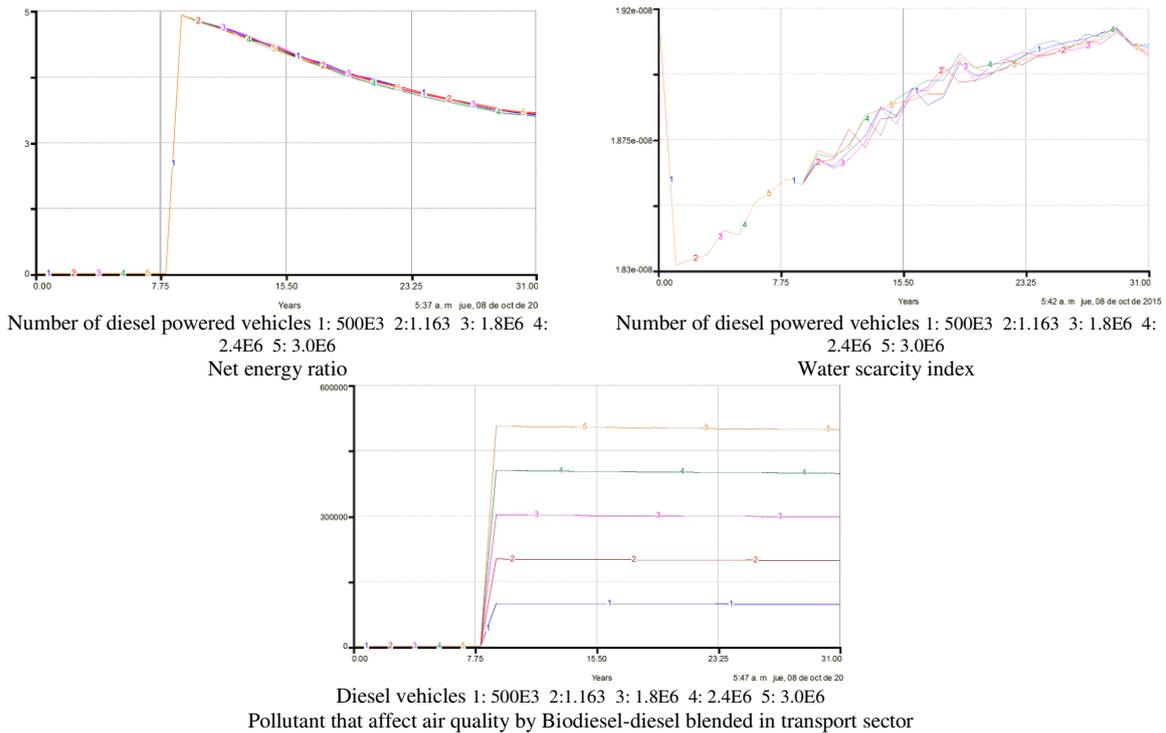
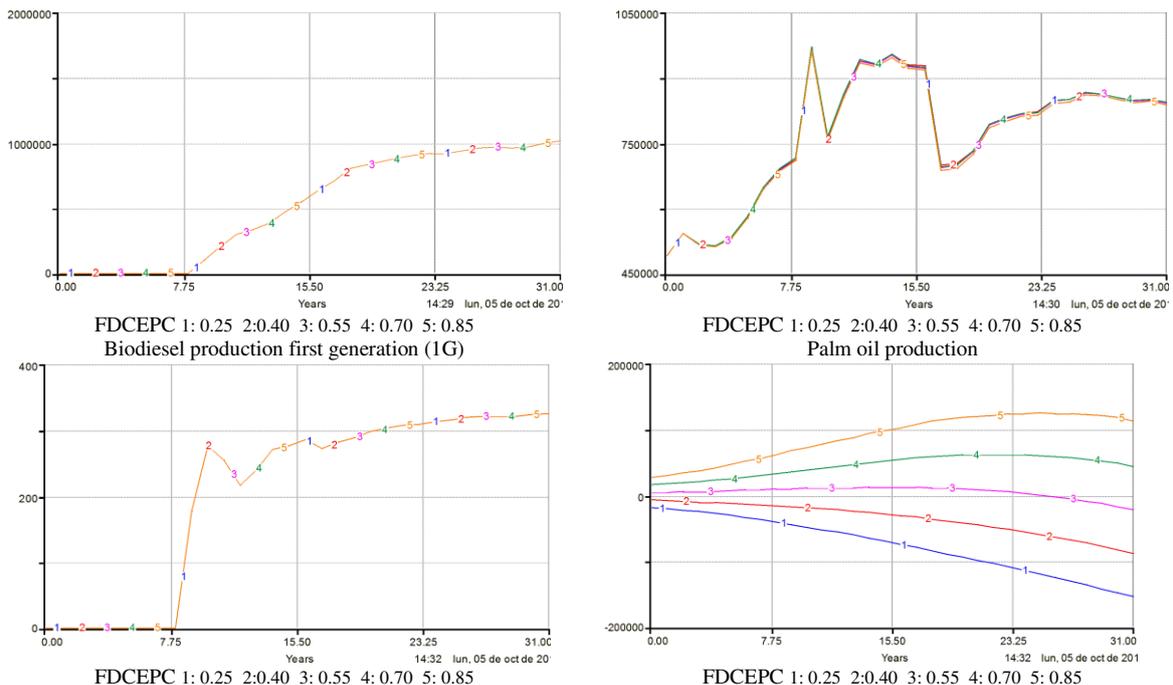


Figure 4-20 Sensitivity analyse of diesel vehicles on the output indicators

4.2.3 Factor of direct contracted employees in oil palm cultivation – FDCEPC

Figure 4-21 provides the incremental ranges for the effect of the FDCEPC on six output indicators (endogenous). Results indicate that if FDCEPC increases, quality of employment in palm cultivation will increase too. This improvement of the social indicator will encourage the palm oil production, while the food security indicator will slightly increase as shown in Figure 4-21. Better quality of employment is linked to better quality of life and local development.



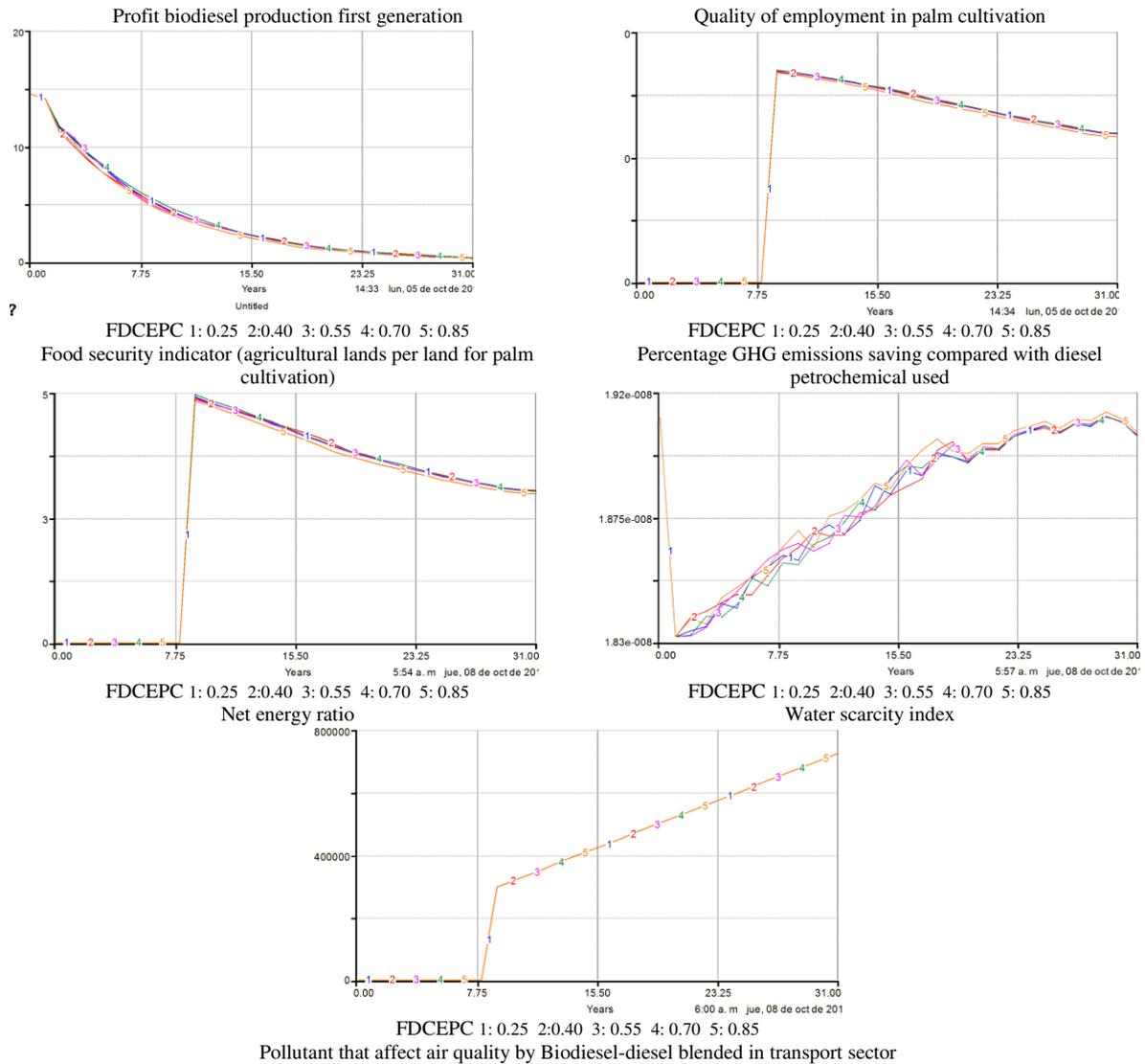


Figure 4-21 Sensitivity analyse of FDCEPC on the output indicators

4.2.4 Costs linked to biodiesel policy

Figure 4-22 provides the incremental range for the effect of costs linked to biodiesel politics on six output indicators (endogenous). Results indicate that if Colombian government supports biodiesel sector, the costs linked to biodiesel policy will increase. As a consequence, first generation biodiesel production, palm-oil production and biodiesel profitability will increase too. This behavior confirms the economic dimension analysis conducted in the SD model on baseline condition. It reflects the effect of Colombian government control on biodiesel market, to ensure biodiesel production profitability. The other output indicators are not sensitive to cost linked to biodiesel policy.

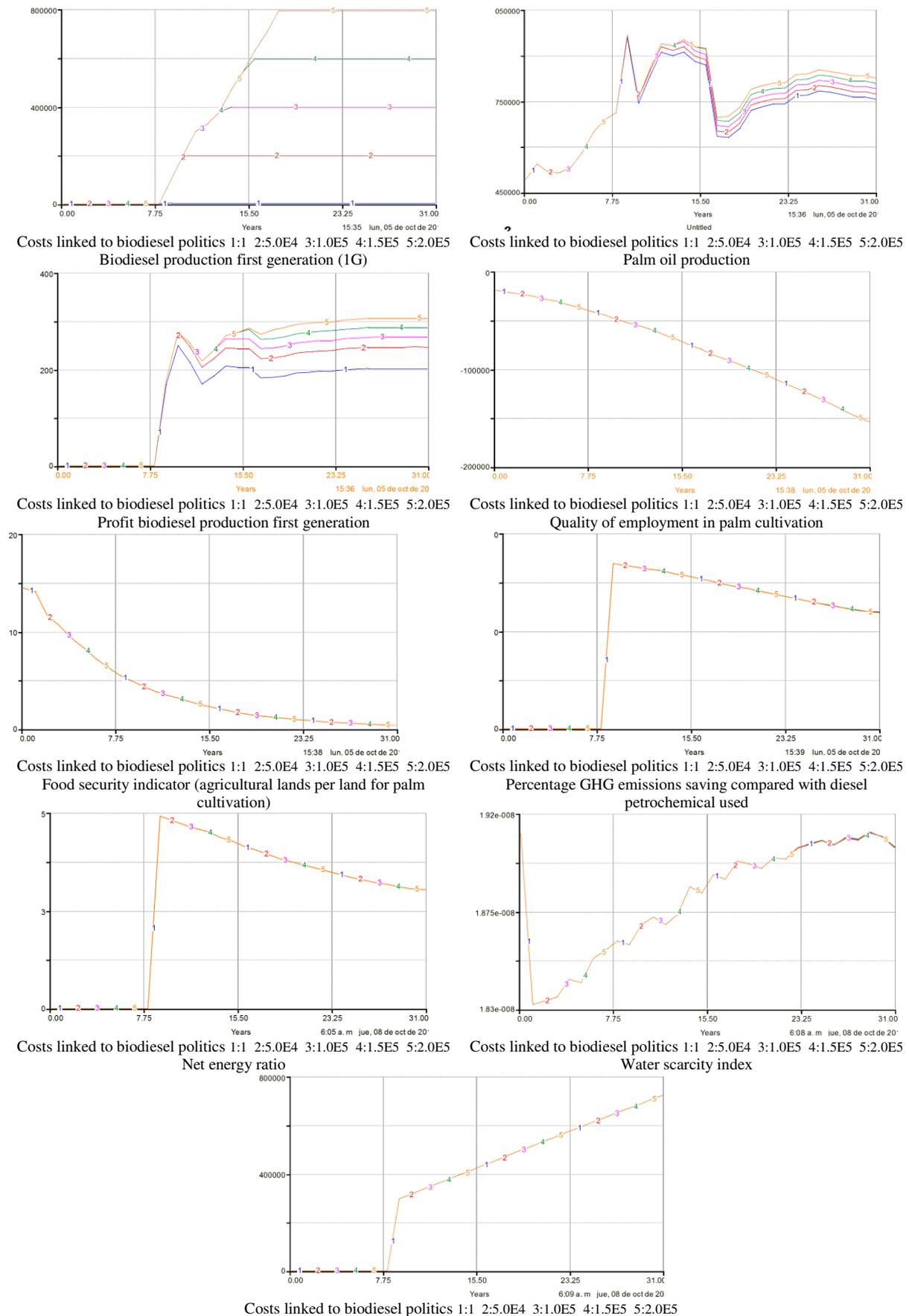
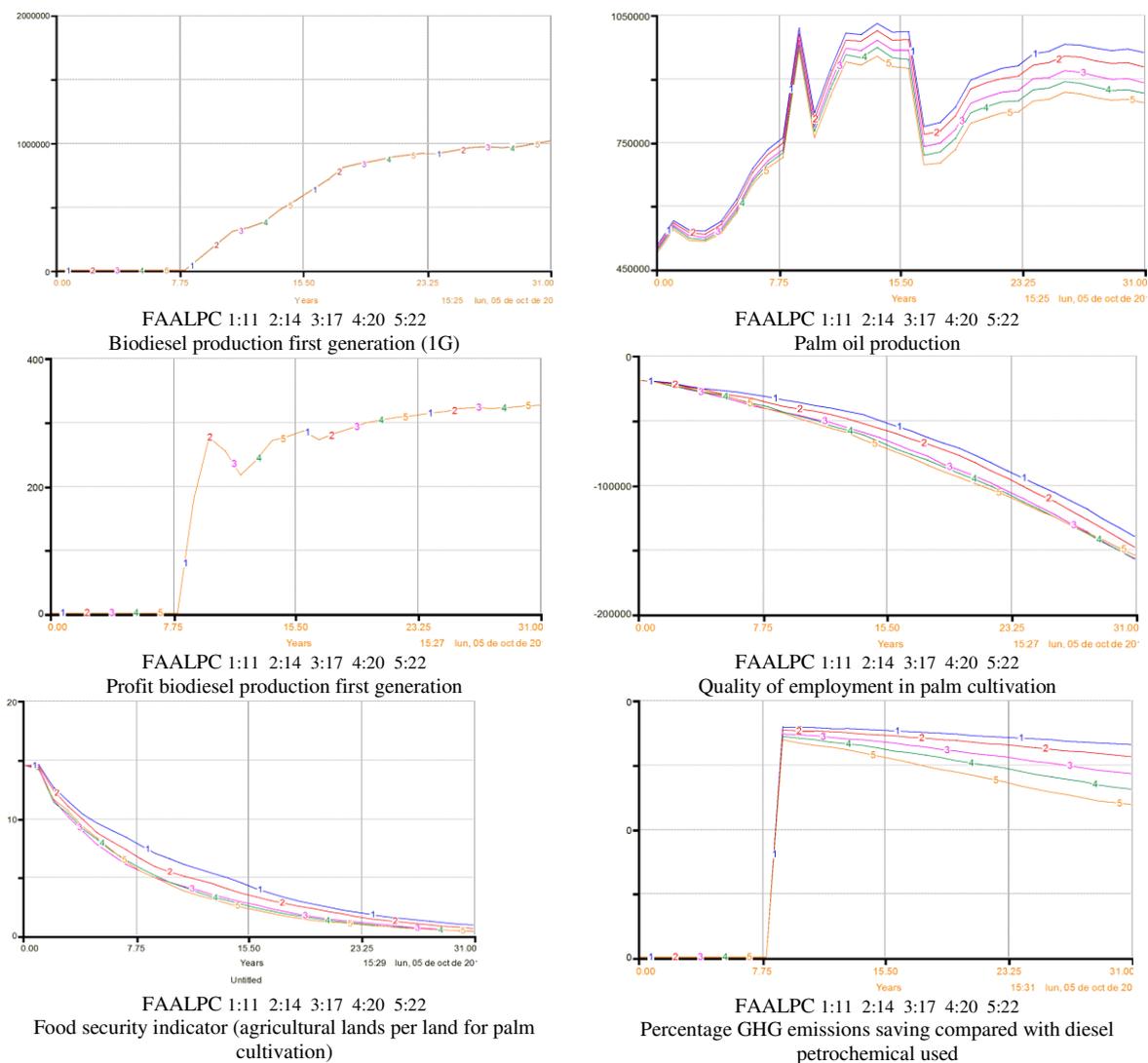


Figure 4-22 Sensitivity analyse of cost linked to biodiesel politics on the output indicators

4.2.5 Factor of agrochemicals applied in land for palm cultivation – FAALPC

Figure 4-23 provides the incremental range for the effect of FAALPC on six output indicators (endogenous). Results indicate that if agrochemicals applied in land increase, the indicators palm oil production, quality of employment, food security index and percentage of GHG emission saving will decrease. This is due because if agrochemicals applied increase, soil loss will rise and crop yield in palm cultivation will diminish. As a consequence, lands for palm cultivation and palm oil production will diminish. On the other hand, these trends will have positive effects on food security index and quality of employment.



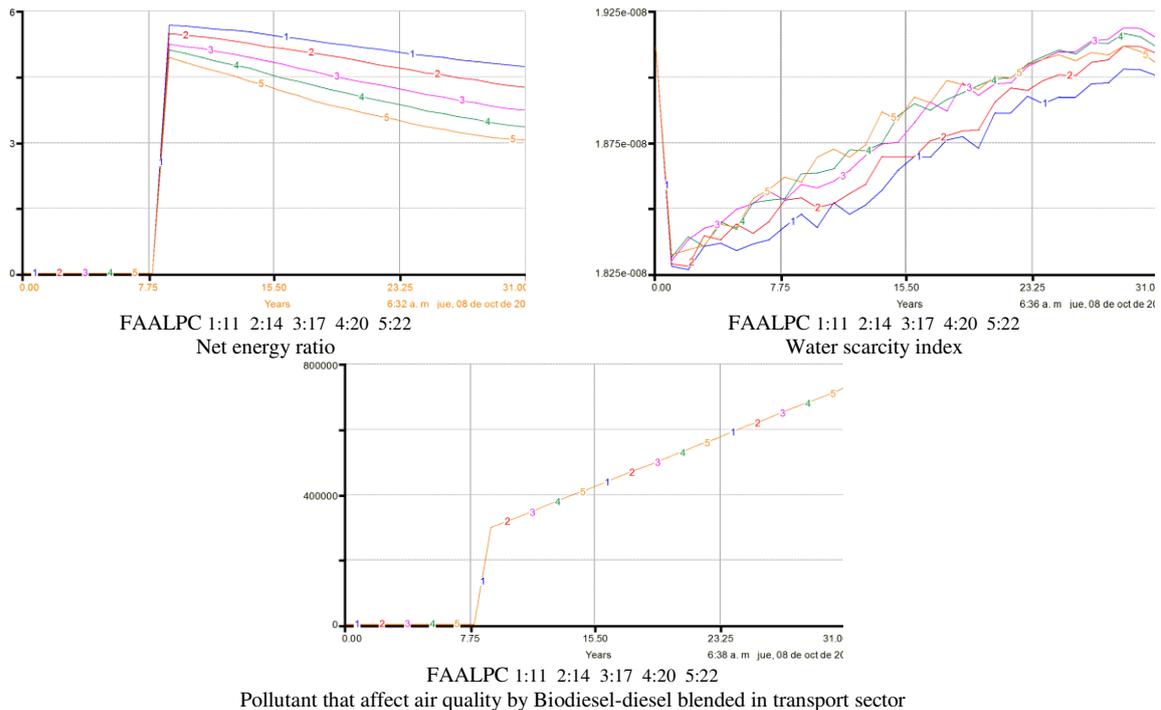
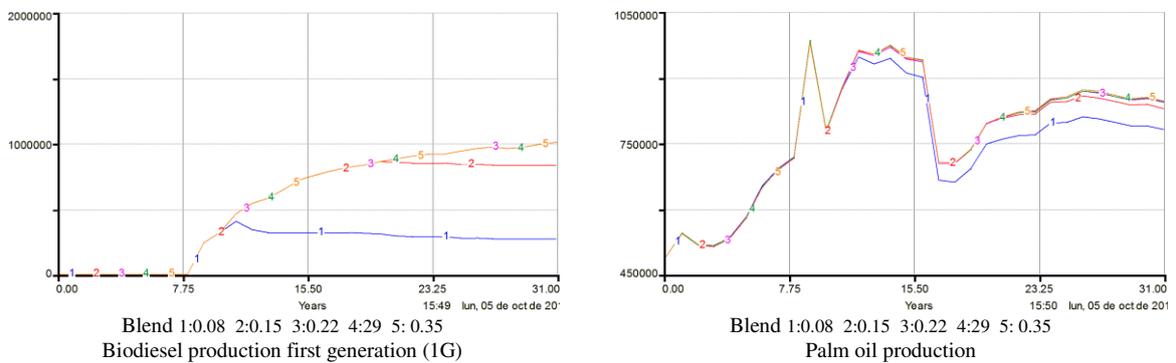


Figure 4-23 Sensitivity analyse of factor agrochemical applied in oil palm cultivation on the output indicators

4.2.6 Biodiesel-diesel blend (Mix ratio)

Figure 4-24 shows that if the biodiesel-diesel blend increases, the biodiesel production, palm oil production and biodiesel production profitability will rise. On the other hand, food security indicator, quality of employment and GHG emission saving will not be improved. Another result is that an increment in the blend, higher than 0.22 (22%), does not generate sensitive changes on the output indicators mentioned before. The blend is defined by Colombian government and it does not respond to demand and supply laws.



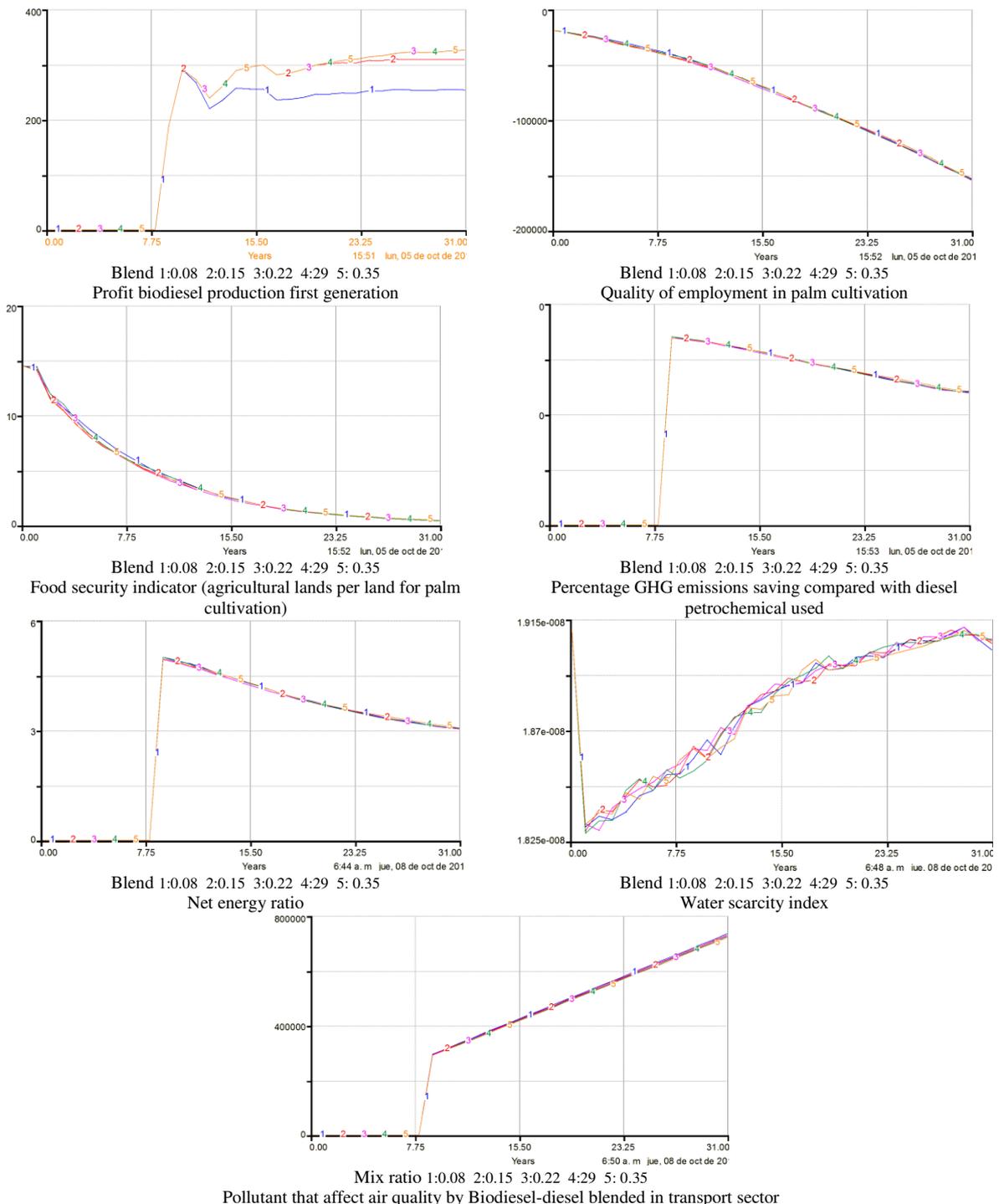
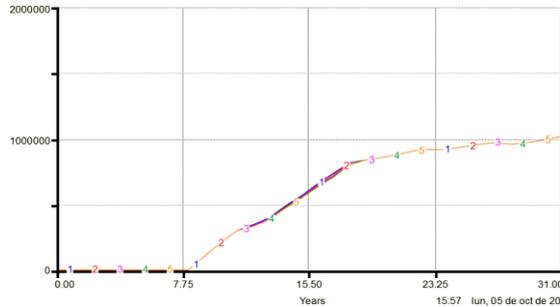


Figure 4-24 Sensitivity analyse of mix ratio biodiesel -diesel on the output indicators

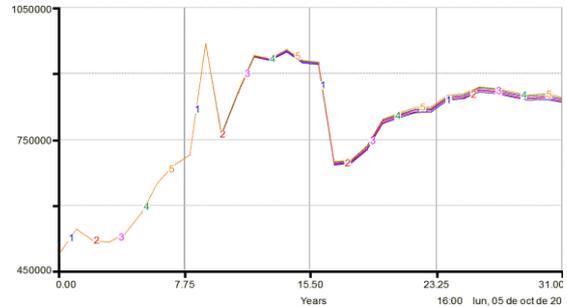
4.2.7 Technological efficiency factor of first generation biodiesel (palm-oil consumed per biodiesel produced)

Figure 4-25 shows that if the technological efficiency factor decreases, which means that less palm oil is required to produce the same quantity of biodiesel, biodiesel production profitability and GHG emissions saving will increase. Biodiesel production profitability and biodiesel production costs have a high dependency on palm oil price. Thus, if fewer raw materials are

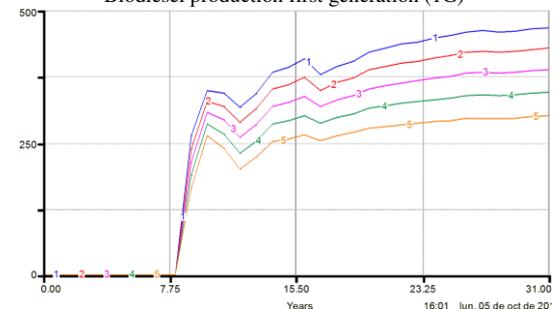
needed, production costs will decrease and biodiesel profitability will be higher. In the same way, GHG emission saving will rise. Fewer raw materials are needed and less land for palm cultivation are required. The other output indicators are not sensitive to technology efficiency factor.



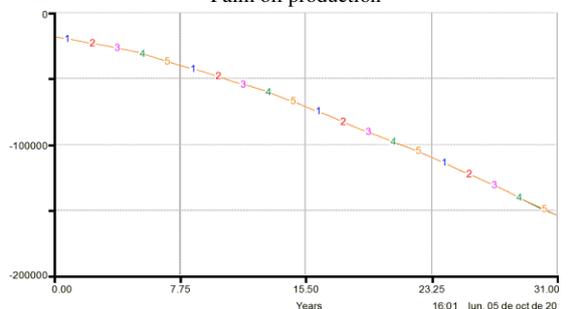
Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Biodiesel production first generation (IG)



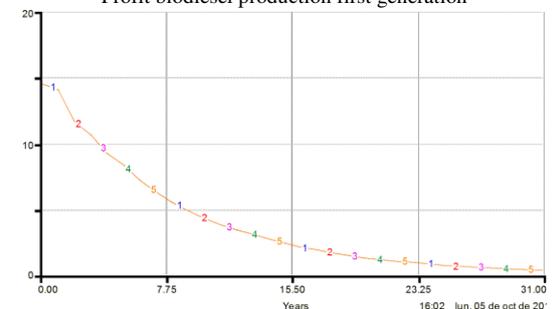
Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Palm oil production



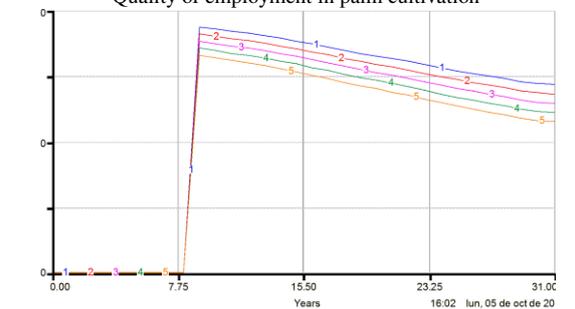
Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Profit biodiesel production first generation



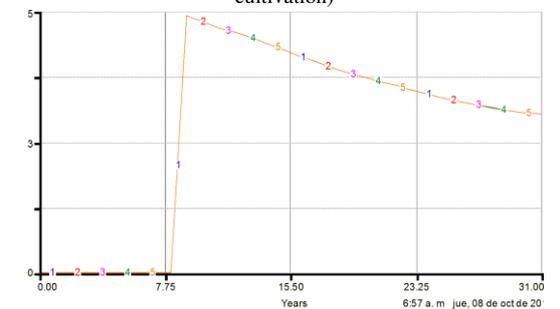
Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Quality of employment in palm cultivation



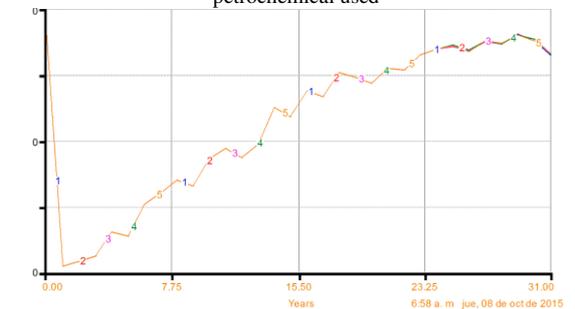
Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Food security indicator (agricultural lands per land for palm cultivation)



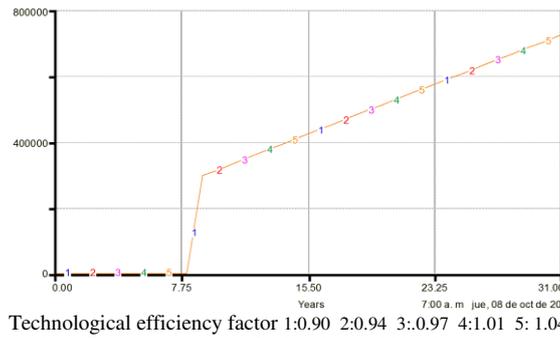
Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Percentage GHG emissions saving compared with diesel petrochemical used



Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Net energy ratio



Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
Water scarcity index

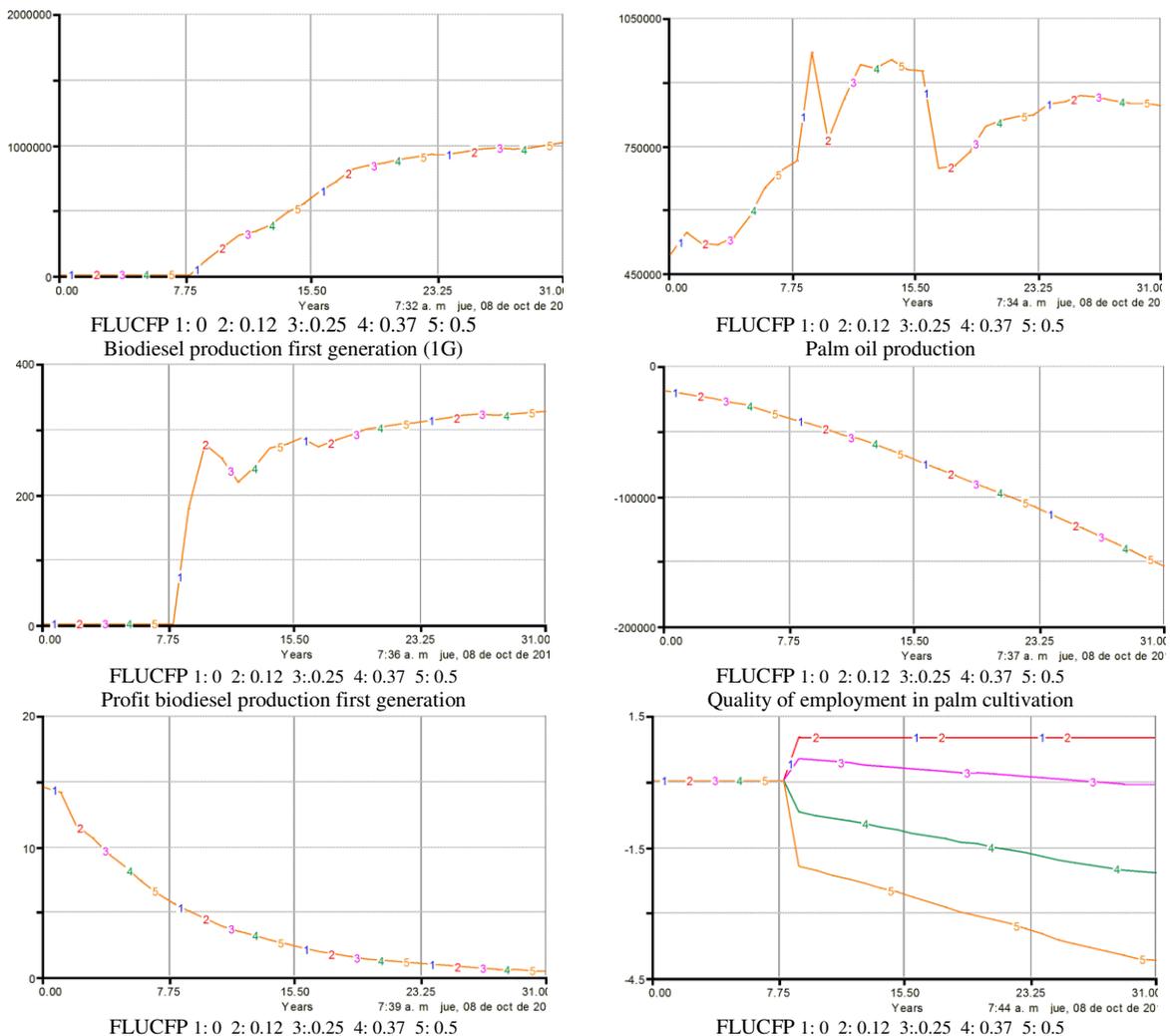


Technological efficiency factor 1:0.90 2:0.94 3:0.97 4:1.01 5: 1.04
 Pollutant that affect air quality by Biodiesel-diesel blended in transport sector

Figure 4-25 Sensitivity analyse of efficiency factor technological on the output indicators

4.2.8 Factor of land use change of rain forest to oil palm cultivation - FLUCFP

Figure 4-26 shows the incremental range for the effect of the factor of land use change of rain forest to oil palm cultivation on six output indicators (endogenous). Results indicate that if rain forest land use change rises, GHG emission saving will decrease. This result is expected because rain forests have high carbon stocks, and its land use change produces important emissions of GHG. The other output indicators are not sensitive to the factor of land use change.



FLUCFP 1: 0 2: 0.12 3: 0.25 4: 0.37 5: 0.5
 Biodiesel production first generation (IG)

FLUCFP 1: 0 2: 0.12 3: 0.25 4: 0.37 5: 0.5
 Palm oil production

FLUCFP 1: 0 2: 0.12 3: 0.25 4: 0.37 5: 0.5
 Profit biodiesel production first generation

FLUCFP 1: 0 2: 0.12 3: 0.25 4: 0.37 5: 0.5
 Quality of employment in palm cultivation

FLUCFP 1: 0 2: 0.12 3: 0.25 4: 0.37 5: 0.5

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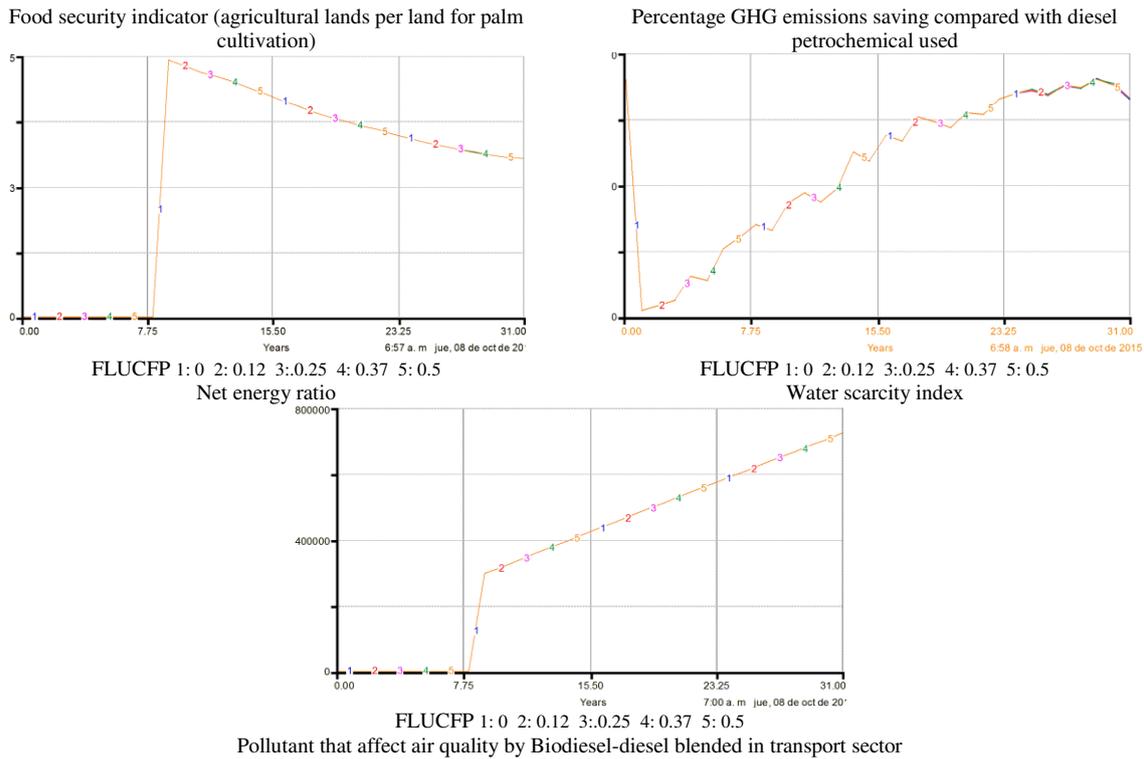


Figure 4-26 Sensitivity analyse of factor of land use change of forest lands to oil palm cultivation on the output indicators

4.2.9 Sensitivity analysis summarized

With the objective to know if each input indicator will be increment what the effect on output indicator sensitivity analysis is conducted. The sensitivity analyses results are summarised in Table 4-2.

Table 4-2 Summary of sensitivity analysis (sensitivity kind: no sensitive, law increment, high increment, law diminish, high diminish)

Output Input	Biodiesel production	Palm oil production	Profit biodiesel	Quality of employment	Food security	GHG saving	NER	Water scarcity	Pollution emission
Oil price	No sensitive	high increment	high increment	No sensitive	No sensitive	No sensitive	No sensitive	No sensitive	No sensitive
Diesel vehicles	No sensitive	Law increment	No sensitive	Law increment	Law increment	Law increment	Law increment	high increment	high increment
Employment factor	No sensitive	Law increment	No sensitive	high increment	Law increment	Law increment	Law increment	Law increment	No sensitive
Cost linked biodiesel politics	high increment	high increment	high increment	No sensitive	No sensitive	No sensitive	No sensitive	No sensitive	No sensitive
Agrochemical factor	No sensitive	high diminish	No sensitive	high increment	high diminish	high increment	high diminish	high increment	No sensitive
Mix ratio	high increment	high increment	Law increment	Law increment	Law increment	Law increment	Law increment	Law increment	Law diminish
Efficiency factor	No sensitive	Law increment	high increment	No sensitive	No sensitive	high increment	No sensitive	No sensitive	No sensitive
Land use change factor	No sensitive	No sensitive	No sensitive	No sensitive	No sensitive	high diminish	No sensitive	No sensitive	No sensitive

4.3 Scenario analysis

Based on sensibility analyses results, the input indicators conditions that promote or discourage sustainable biodiesel production are identified (refer Table 4-1). Consequently, optimistic and

pessimistic scenarios are proposed. The input indicators will be increased or reduced simultaneously in each scenario and then, the SD model response will be analysed and discussed.

4.3.1 Optimistic scenario

In this scenario the simulation condition that promotes a sustainable biodiesel production are described (Table 4-3). Optimistic scenario considers the following conditions:

Economic dimension: oil price and the number of diesel powered vehicles will increment.

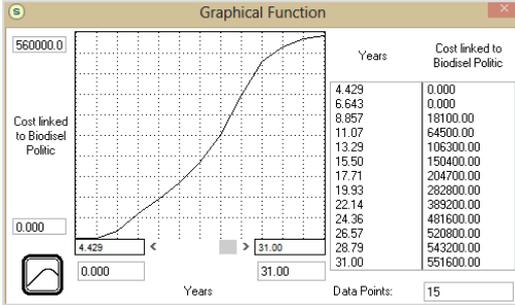
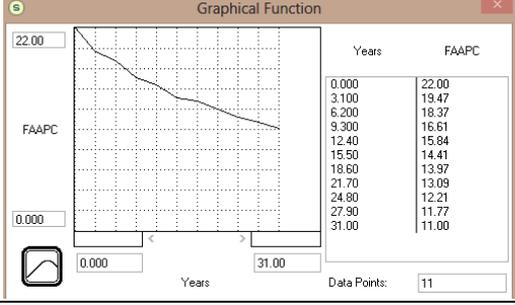
Social dimension: factor of direct contracted employees in palm cultivation will increase.

Environmental dimension: factor of agrochemicals applied in land for palm cultivation will diminish as well as the factor of land use change of forest lands to oil palm cultivation.

Political dimension: costs linked to biodiesel policies and blend biodiesel-diesel will increase.

Technological dimension: the efficiency factor of first generation biodiesel will be improved, valorization of glycerol by PDO will be implemented, and biodiesel production of second and third generation in Colombia will be promoted.

Table 4-3 Optimistic scenario conditions

Input indicators (exogenous)	Units	Range																												
Oil price	USD/t	[150 - 850]																												
Diesel vehicles	Dimensionless	[605,000 – 2,300,000]																												
Factor of direct contrasts employees in palm cultivation	Dimensionless	[0.25 – 0.85]																												
Costs linked to biodiesel politics	USD	 <table border="1"> <thead> <tr> <th>Years</th> <th>Cost linked to Biodiesel Poltic</th> </tr> </thead> <tbody> <tr><td>4.429</td><td>0.000</td></tr> <tr><td>6.643</td><td>0.000</td></tr> <tr><td>8.857</td><td>18100.00</td></tr> <tr><td>11.07</td><td>64500.00</td></tr> <tr><td>13.29</td><td>106300.00</td></tr> <tr><td>15.50</td><td>150400.00</td></tr> <tr><td>17.71</td><td>204700.00</td></tr> <tr><td>19.93</td><td>262800.00</td></tr> <tr><td>22.14</td><td>389200.00</td></tr> <tr><td>24.36</td><td>481600.00</td></tr> <tr><td>26.57</td><td>520800.00</td></tr> <tr><td>28.79</td><td>543200.00</td></tr> <tr><td>31.00</td><td>551600.00</td></tr> </tbody> </table>	Years	Cost linked to Biodiesel Poltic	4.429	0.000	6.643	0.000	8.857	18100.00	11.07	64500.00	13.29	106300.00	15.50	150400.00	17.71	204700.00	19.93	262800.00	22.14	389200.00	24.36	481600.00	26.57	520800.00	28.79	543200.00	31.00	551600.00
Years	Cost linked to Biodiesel Poltic																													
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Factor of agrochemicals applied in land for palm cultivation	t agrochemical / ha	 <table border="1"> <thead> <tr> <th>Years</th> <th>FAAPC</th> </tr> </thead> <tbody> <tr><td>0.000</td><td>22.00</td></tr> <tr><td>3.100</td><td>19.47</td></tr> <tr><td>6.200</td><td>18.37</td></tr> <tr><td>9.300</td><td>16.61</td></tr> <tr><td>12.40</td><td>15.84</td></tr> <tr><td>15.50</td><td>14.41</td></tr> <tr><td>18.60</td><td>13.97</td></tr> <tr><td>21.70</td><td>13.09</td></tr> <tr><td>24.80</td><td>12.21</td></tr> <tr><td>27.90</td><td>11.77</td></tr> <tr><td>31.00</td><td>11.00</td></tr> </tbody> </table>	Years	FAAPC	0.000	22.00	3.100	19.47	6.200	18.37	9.300	16.61	12.40	15.84	15.50	14.41	18.60	13.97	21.70	13.09	24.80	12.21	27.90	11.77	31.00	11.00				
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27.90	11.77																													
31.00	11.00																													
Mix ratio biodiesel-diesel	Dimensionless	[0.08 – 0.35]																												

Input indicators (exogenous)	Units	Range																												
Technological efficiency factor of first generation biodiesel (tons palm oil per tons of biodiesel)	Dimensionless	<p>Increase of 1.02 in 2008 to 0.9 in 2030</p> <table border="1"> <thead> <tr> <th>Years</th> <th>EFOPperBd</th> </tr> </thead> <tbody> <tr><td>2.385</td><td>1.020</td></tr> <tr><td>4.769</td><td>1.020</td></tr> <tr><td>7.154</td><td>1.020</td></tr> <tr><td>9.538</td><td>1.020</td></tr> <tr><td>11.92</td><td>1.020</td></tr> <tr><td>14.31</td><td>1.010</td></tr> <tr><td>16.69</td><td>1.000</td></tr> <tr><td>19.08</td><td>0.980</td></tr> <tr><td>21.46</td><td>0.960</td></tr> <tr><td>23.85</td><td>0.940</td></tr> <tr><td>26.23</td><td>0.910</td></tr> <tr><td>28.62</td><td>0.902</td></tr> <tr><td>31.00</td><td>0.900</td></tr> </tbody> </table>	Years	EFOPperBd	2.385	1.020	4.769	1.020	7.154	1.020	9.538	1.020	11.92	1.020	14.31	1.010	16.69	1.000	19.08	0.980	21.46	0.960	23.85	0.940	26.23	0.910	28.62	0.902	31.00	0.900
Years	EFOPperBd																													
2.385	1.020																													
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31.00	0.900																													
Factor of land use change of forest lands to oil palm cultivation	Dimensionless	<table border="1"> <thead> <tr> <th>Years</th> <th>LUC of forest to Palm Cultivation</th> </tr> </thead> <tbody> <tr><td>0.000</td><td>0.230</td></tr> <tr><td>3.100</td><td>0.203</td></tr> <tr><td>6.200</td><td>0.181</td></tr> <tr><td>9.300</td><td>0.160</td></tr> <tr><td>12.40</td><td>0.143</td></tr> <tr><td>15.50</td><td>0.130</td></tr> <tr><td>18.60</td><td>0.119</td></tr> <tr><td>21.70</td><td>0.114</td></tr> <tr><td>24.80</td><td>0.112</td></tr> <tr><td>27.90</td><td>0.109</td></tr> <tr><td>31.00</td><td>0.107</td></tr> </tbody> </table>	Years	LUC of forest to Palm Cultivation	0.000	0.230	3.100	0.203	6.200	0.181	9.300	0.160	12.40	0.143	15.50	0.130	18.60	0.119	21.70	0.114	24.80	0.112	27.90	0.109	31.00	0.107				
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There are valorization of glycerol by PDO																														
There are biodiesel productions of second and third generation in Colombia.																														
There are diminutions of oil palm cultivation as a consequence of biodiesel production of second and third generation in Colombia.																														

4.3.1.1 Economic dimension

Figure 4-27 shows the results of the optimistic scenario, in which biodiesel production will be 1,855,000 t in 2030 and biodiesel production capacity will be 2,190,000 t at the same year. In baseline scenario both economic indicators in 2030 will increase up to 988,000 t. These economic indicators are highly influenced by Colombia governmental support, described through the increment in the costs linked to biodiesel policy and blend biodiesel-diesel.

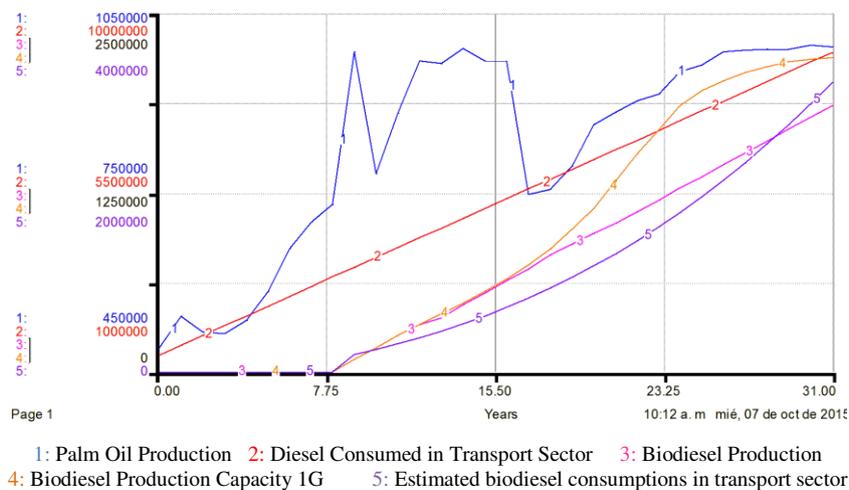
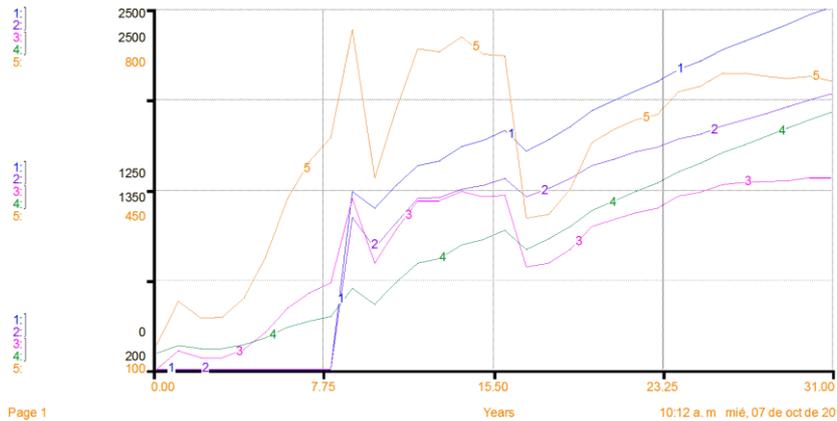


Figure 4-27 Graphical output of economic indicators of model in optimistic scenario

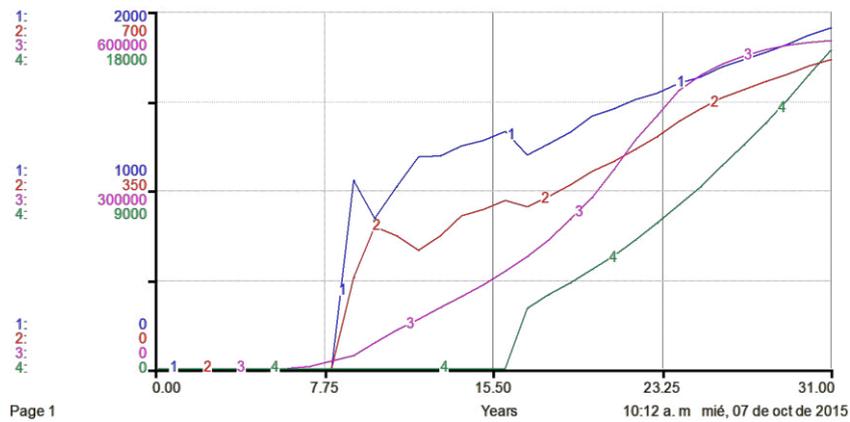
In optimistic scenario oil price will increase, so palm-oil price will increase too. As a consequence, biodiesel production costs will increase, and Colombian government will have to increase biodiesel price with the aim to ensure biodiesel profitability. Another effect if biodiesel price rises is that diesel price might follow the same trend, which could result in higher transportation costs.



1: Biodiesel Price 2: Biodiesel Production Costs 3: Diesel Price 4: Palm Oil Price 5: Oil Price

Figure 4-28 Graphical output of economic indicators of model in optimistic scenario

A relevant change in this optimistic scenario is related to increment in biodiesel profitability in comparison to baseline scenario and the valorization of glycerol by PDO as shown in Figure 4-29. Valorization of glycerol can be added to biodiesel profitability and private investors could be more interested in develop projects to increment biodiesel production capacity.



1: Biodiesel Production Costs 2: Profit Biodiesel Production 3: Cost linked to Biodiesel Politic 4: Valorization of glycerol by PDO

Figure 4-29 Graphical output of economic indicators of model in optimistic scenario

4.3.1.2 Social dimension

Despite the increment of the Colombian governmental support to biodiesel sector, in this scenario, characterized by increments in the oil price and in the blend biodiesel - diesel, social indicators such as population displaced by violence, land concentration index, poor population

and food security indicator, will have similar behaviors that in baseline scenario, as is shown in Figure 4-30. Regarding palm-oil cultivation there will be a slight reduction at the end of the period, as a consequence of the beginning of the production of second and third generation biodiesel. However, significant positive changes will be observed in the quality of employment as shown in Figure 4-31, due to better contract conditions of direct employees.

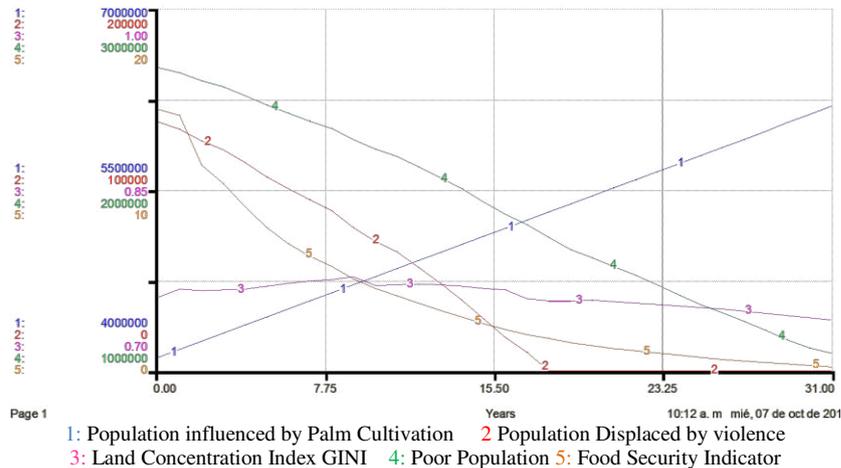


Figure 4-30 Graphical output of social indicators of model in optimistic scenario

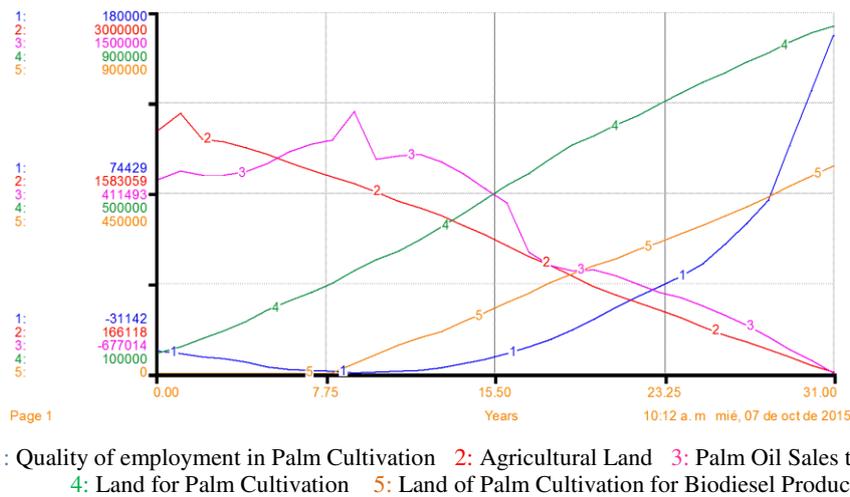
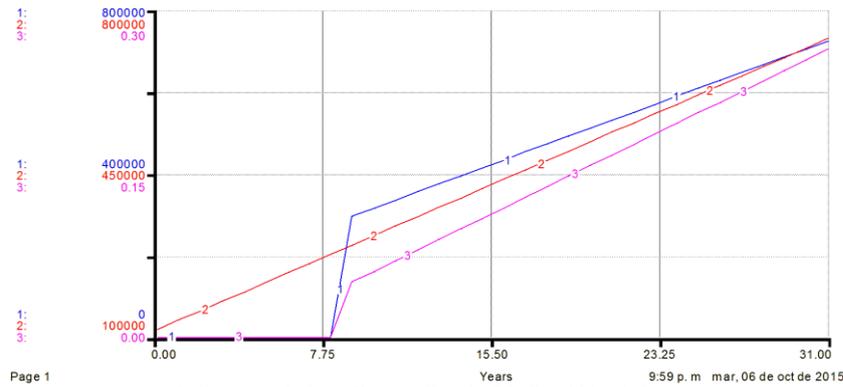


Figure 4-31 Graphical output of social indicators of model in optimistic scenario

4.3.1.3 Environmental dimension

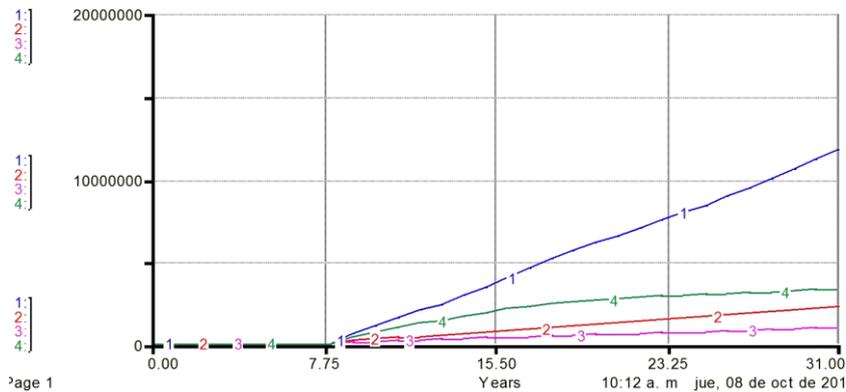
Regarding pollutant emissions effecting air quality by biodiesel and diesel blended, despite the fact that the blend biodiesel- diesel will be increased, the content of air pollutants will not be reduced in the long run, and it will have a similar trend than in the baseline scenario (Figure 4-32). The reason is the increment in the number of diesel powered vehicles.



1: Pollutant emission affect quality air: Biodiesel blended
 2: Pollutant emission affect quality air: Diesel 100% 3: Mix Ratio Biodiesel and diesel blended

Figure 4-32 Graphical output of environmental indicators of model in optimistic scenario

With reference to GHG emissions along the life cycle of biodiesel production, in the optimistic scenario they are linked to land use change and they will be reduced in comparison to the baseline scenario. The reason is that land use change of rain forests to palm-oil cultivation will diminish. Another positive effect of this diminution of land use change is that the percentage of GHG emissions saving will be 100%, as shown in Figure 4-34. This means that all GHG emission in life cycle of biodiesel production are saving.



1: GHG Absorption in oil palm cultivation 2: GHG by biodiesel production and supply chain transport
 3: GHG by oil palm cultivation and palm oil extraction 4: GHG by direct land use change

Figure 4-33 Graphical output of environmental indicators of model in optimistic scenario

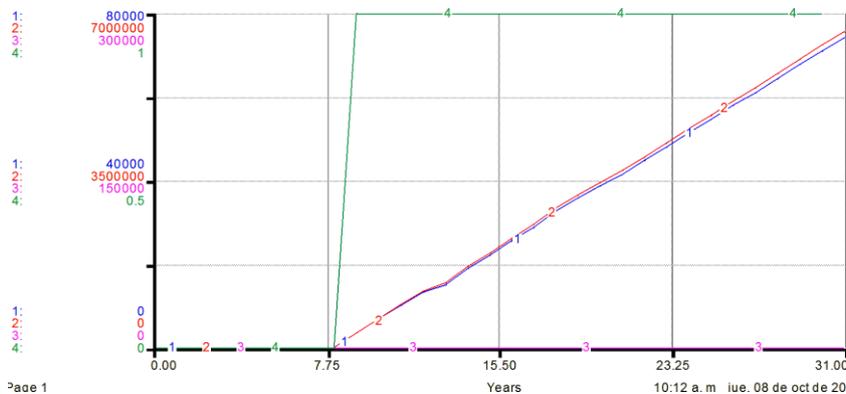


Figure 4-34 Graphical output of environmental indicators of model in optimistic scenario

Moreover, despite biodiesel production will increase to 1,800,000 t in 2030 in the optimistic scenario, lands for oil palm cultivation will increase in proportion similar to the predicted in the

baseline conditions (Figure 4-35). This is an important result, explained by two conditions. First, the technological efficiency factor of first generation biodiesel will improve, diminishing the palm oil demand. Second, as a consequence, agrochemicals applied in oil palm cultivation and soil loss will diminish, while crop yield will augment (4.1 tons of palm oil per hectare in 1999 to 3.2 in 2030 as shown in Figure 4-36, in comparison to 4.1 tons of palm oil per hectare in 1999 to 2.1 in 2030 in the baseline scenario).

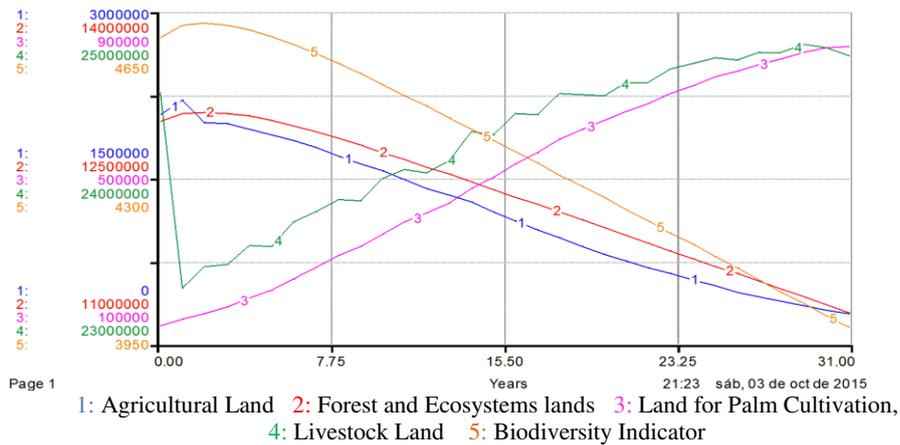


Figure 4-35 Graphical output of environmental indicators of model in optimistic scenario

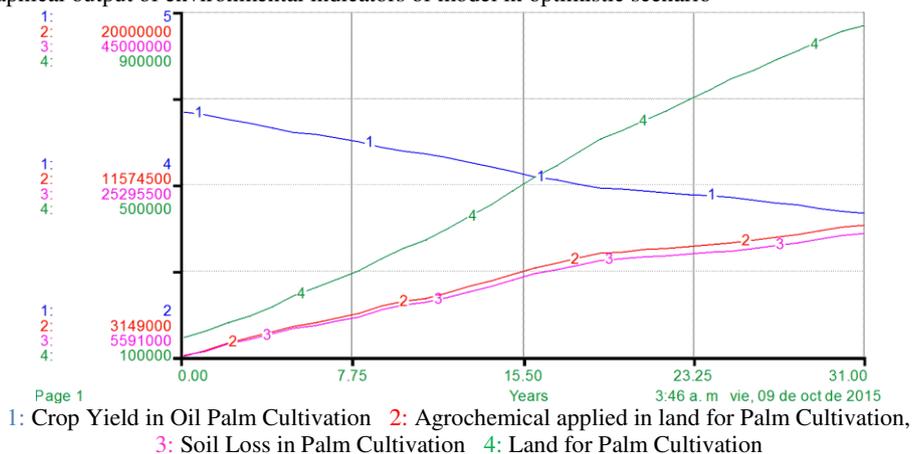


Figure 4-36 Graphical output of environmental indicators of model in optimistic scenario

About the water scarcity index, it will slightly increase in the optimistic scenario as shown in Figure 4-37. This behaviour is explained, principally, by the increment in water demand in livestock lands (Figure 4-37). Also, palm oil extraction and biodiesel production will increment water demand because biodiesel production will augment as shown in Figure 4-38. With respect to energy output, it will slightly rise in comparison to baseline scenario as shown in Figure 4-39. The explanation is the same of the water scarcity index.

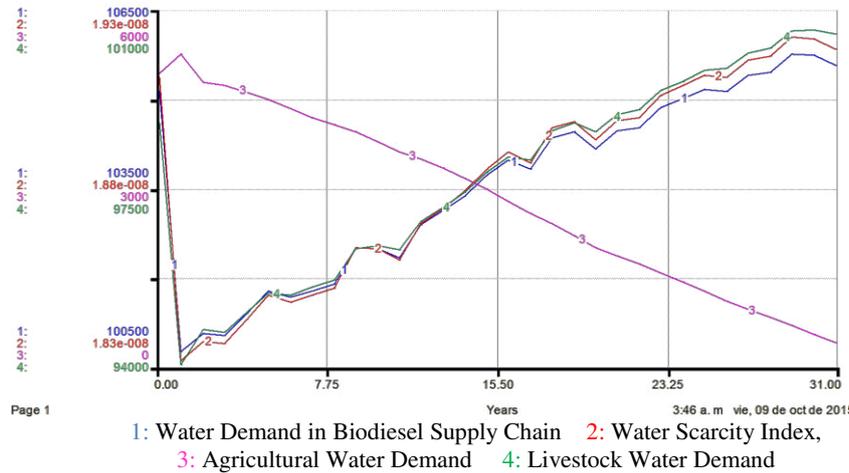


Figure 4-37 Graphical output of environmental indicators of model in optimistic scenario

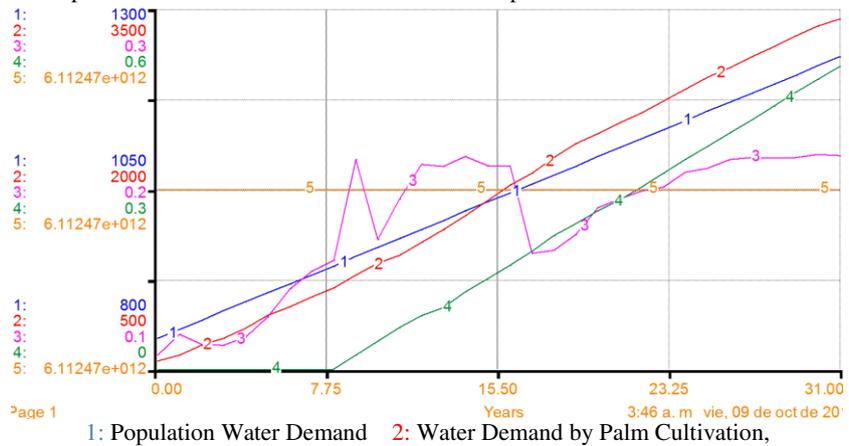


Figure 4-38 Graphical output of environmental indicators of model in optimistic scenario

With respect to energy output, it will slightly rise in comparison to baseline scenario as shown in Figure 4-39.

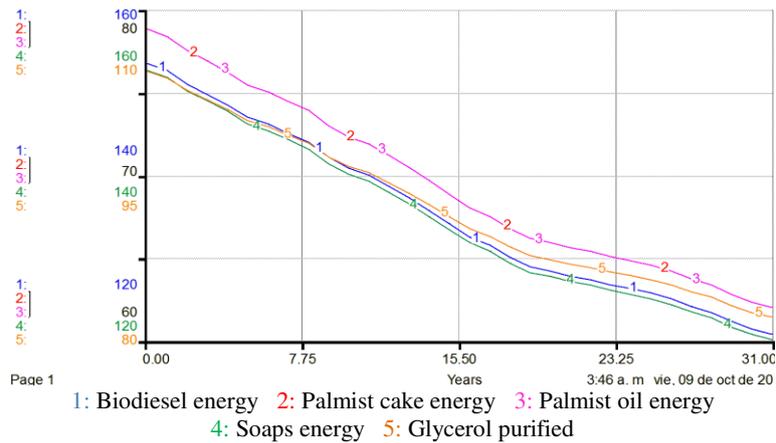
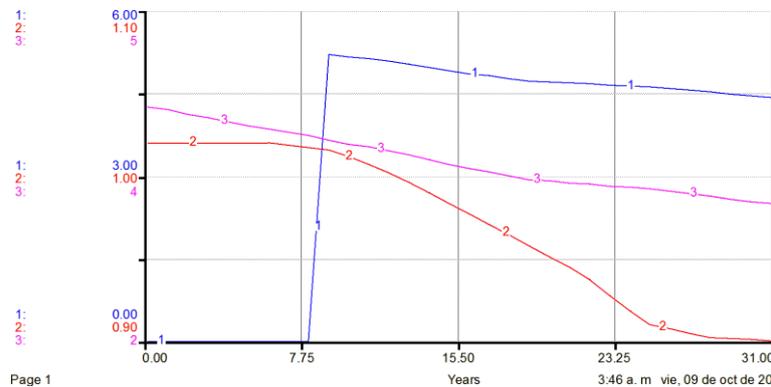


Figure 4-39 Graphical output of environmental indicators of model in optimistic scenario

Under optimistic conditions it is observed a better result in the net energy ratio- NER (5.2 in 2008 to 4.3 in 2030, Figure 4-40) in comparison to baseline condition (4.9 in 2008 to 2.9 in 2030). Based on sensitivity analysis, net energy ratio improves if agrochemicals applied to

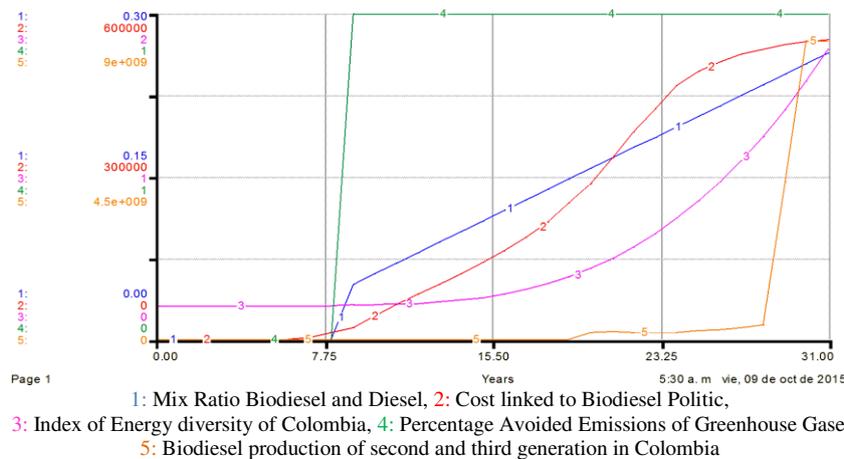
palm-oil cultivation will diminish, which promotes that crop yield will increase. Further, if the blend biodiesel - diesel rises, the NER will rise too.



1: Net energy ration 2: Efficiency factor of palm oil tone per biodiesel tone 3: Crop yield in palm cultivation
 Figure 4-40 Graphical output of environmental indicators of model in baseline scenario

4.3.1.4 Political dimension

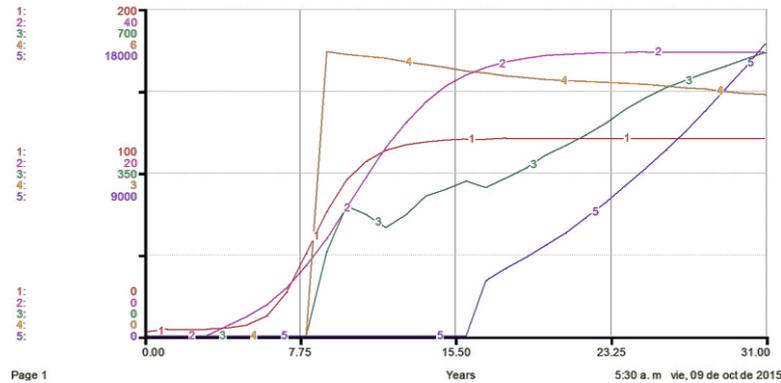
In baseline and optimist scenarios the blend biodiesel–diesel will increase from 0.08 in 2008 to 0.26 in 2030, duplicating the costs linked to biodiesel policy. With relation to biodiesel production of second and third generation, three facts have effect on them: the governmental support to local development, the increase in the biodiesel production and the international production of biodiesel of the second and third generation. Then, Colombia will start the production of these types of biodiesel by 2018. This fact will have a positive effect in diminishing the land use change of rain forest and ecosystem to palm-oil cultivation. As a consequence, the GHG savings will increase significantly. The behavior of the policy indicators in the optimistic conditions are displayed in Figure 4-41.



1: Mix Ratio Biodiesel and Diesel, 2: Cost linked to Biodiesel Politic,
 3: Index of Energy diversity of Colombia, 4: Percentage Avoided Emissions of Greenhouse Gases
 5: Biodiesel production of second and third generation in Colombia
 Figure 4-41 Graphical output of politic indicators of model in optimistic scenario

4.3.1.5 Technological dimension

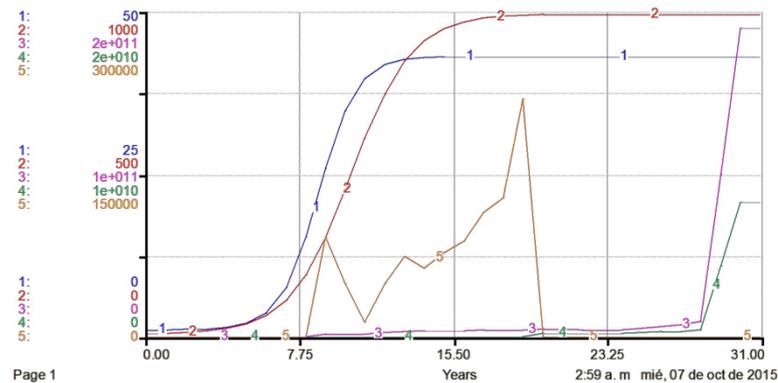
Technological indicators in optimistic scenario are shown in Figure 4-42 and Figure 4-43. The main observed effect is related to the profitability of biodiesel production. Biodiesel profitability will increase as a consequence of the oil price, the cost linked to biodiesel policy and efficiency factor behavior, previously described. Similar to the baseline condition, profitability by valorization of glycerol can be added to biodiesel profitability.



1: Articles in Journal scientific about Biodiesel production 1G 2: Patents about Biodiesel production 1G
3: Profit of biodiesel production 4: Net energy ratio 5: Profit of valorization glycerol through PDO

Figure 4-42 Graphical output of technological indicators of model in optimistic scenario

The technological maturity trend related to patents and articles in scientific journals about second and third generation biodiesel production shown in Figure 4-43, can be linked to research and development investment. This condition promotes virtuous cycles improving biodiesel profitability by by-products valorisations.



1: Patents about Biodiesel production 2G and 3G 2: Articles in journal scientific about Biodiesel production 2G and 3G
3: International Production of Biodiesel 2G and 3G 4: Colombian biodiesel production of 2G and 3G
5: Unsatisfied demand of biodiesel in transport sector

Figure 4-43 Graphical output of technological indicators of model in optimistic scenario

4.3.2. Pessimistic scenario

The simulation conditions that discourage a sustainable biodiesel production are described in Figure 4-4 and are summarized as follows:

Economic dimension: oil price and the number of diesel powered vehicles will diminish.

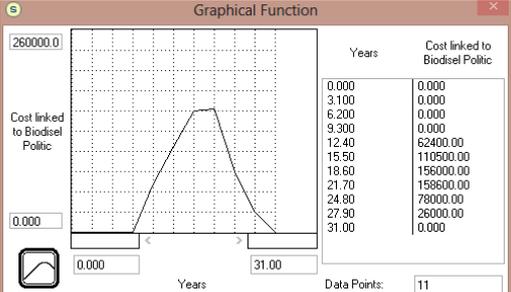
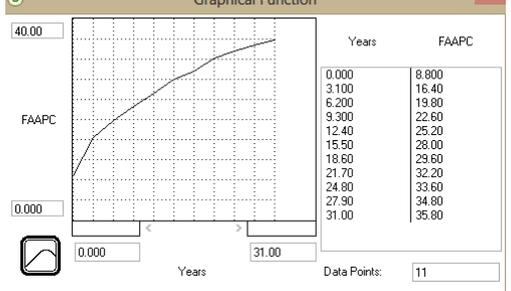
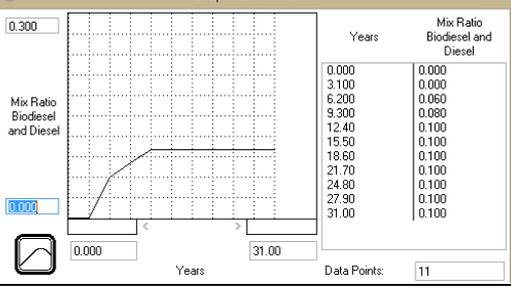
Social dimension: the factor of direct contracted employees in palm cultivation will increase.

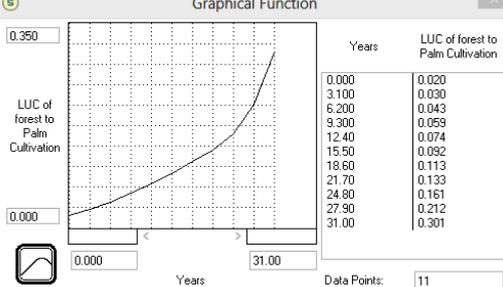
Environmental dimension, the factor of agrochemicals applied in land for palm cultivation and the factor of land use change of forest lands to oil palm cultivation will decrease.

Political dimension: costs linked to biodiesel politics will be reduced and mix ratio biodiesel-diesel will keep constant in 0.10 from 2014 to 2030.

Technological dimension: the efficiency factor of first generation biodiesel will be constant (1.04), there will not be valorization of glycerol nor biodiesel production of second and third generation in Colombia.

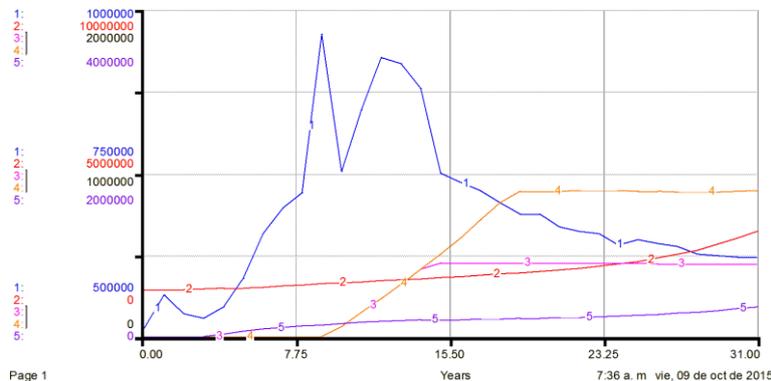
Table 4-4 Pessimistic scenario conditions

Input indicators (exogenous)	Units	Range																								
Oil price	USD/t	[150 - 500]																								
Diesel vehicles	Dimensionless	[605,000 – 1.500,000]																								
Factor of direct contrasts employees in palm cultivation	Dimensionless	[0.25 – 0.05]																								
Costs linked to biodiesel politics	USD	 <table border="1"> <thead> <tr> <th>Years</th> <th>Cost linked to Biodiesel Politic</th> </tr> </thead> <tbody> <tr><td>0.000</td><td>0.000</td></tr> <tr><td>3.100</td><td>0.000</td></tr> <tr><td>6.200</td><td>0.000</td></tr> <tr><td>9.300</td><td>0.000</td></tr> <tr><td>12.40</td><td>62400.00</td></tr> <tr><td>15.50</td><td>110500.00</td></tr> <tr><td>18.60</td><td>158600.00</td></tr> <tr><td>21.70</td><td>158600.00</td></tr> <tr><td>24.80</td><td>78000.00</td></tr> <tr><td>27.90</td><td>26000.00</td></tr> <tr><td>31.00</td><td>0.000</td></tr> </tbody> </table>	Years	Cost linked to Biodiesel Politic	0.000	0.000	3.100	0.000	6.200	0.000	9.300	0.000	12.40	62400.00	15.50	110500.00	18.60	158600.00	21.70	158600.00	24.80	78000.00	27.90	26000.00	31.00	0.000
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Factor of agrochemicals applied in land for palm cultivation	t agrochemical / ha	 <table border="1"> <thead> <tr> <th>Years</th> <th>FAAPC</th> </tr> </thead> <tbody> <tr><td>0.000</td><td>8.800</td></tr> <tr><td>3.100</td><td>16.40</td></tr> <tr><td>6.200</td><td>19.80</td></tr> <tr><td>9.300</td><td>22.60</td></tr> <tr><td>12.40</td><td>25.20</td></tr> <tr><td>15.50</td><td>28.00</td></tr> <tr><td>18.60</td><td>29.60</td></tr> <tr><td>21.70</td><td>32.20</td></tr> <tr><td>24.80</td><td>33.60</td></tr> <tr><td>27.90</td><td>34.80</td></tr> <tr><td>31.00</td><td>35.80</td></tr> </tbody> </table>	Years	FAAPC	0.000	8.800	3.100	16.40	6.200	19.80	9.300	22.60	12.40	25.20	15.50	28.00	18.60	29.60	21.70	32.20	24.80	33.60	27.90	34.80	31.00	35.80
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Mix ratio biodiesel-diesel	Dimensionless	 <table border="1"> <thead> <tr> <th>Years</th> <th>Mix Ratio Biodiesel and Diesel</th> </tr> </thead> <tbody> <tr><td>0.000</td><td>0.000</td></tr> <tr><td>3.100</td><td>0.000</td></tr> <tr><td>6.200</td><td>0.060</td></tr> <tr><td>9.300</td><td>0.080</td></tr> <tr><td>12.40</td><td>0.100</td></tr> <tr><td>15.50</td><td>0.100</td></tr> <tr><td>18.60</td><td>0.100</td></tr> <tr><td>21.70</td><td>0.100</td></tr> <tr><td>24.80</td><td>0.100</td></tr> <tr><td>27.90</td><td>0.100</td></tr> <tr><td>31.00</td><td>0.100</td></tr> </tbody> </table>	Years	Mix Ratio Biodiesel and Diesel	0.000	0.000	3.100	0.000	6.200	0.060	9.300	0.080	12.40	0.100	15.50	0.100	18.60	0.100	21.70	0.100	24.80	0.100	27.90	0.100	31.00	0.100
Years	Mix Ratio Biodiesel and Diesel																									
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31.00	0.100																									
Efficiency factor technological biodiesel first generation tons palm oil per tons of biodiesel	Dimensionless	Constant = 1.04																								

Input indicators (exogenous)	Units	Range																								
Factor of land use change of forest lands to oil palm cultivation	Dimensionless	 <table border="1" data-bbox="1173 268 1356 481"> <thead> <tr> <th>Years</th> <th>LUC of forest to Palm Cultivation</th> </tr> </thead> <tbody> <tr><td>0.000</td><td>0.020</td></tr> <tr><td>3.100</td><td>0.030</td></tr> <tr><td>6.200</td><td>0.043</td></tr> <tr><td>9.300</td><td>0.059</td></tr> <tr><td>12.40</td><td>0.074</td></tr> <tr><td>15.50</td><td>0.092</td></tr> <tr><td>18.60</td><td>0.113</td></tr> <tr><td>21.70</td><td>0.133</td></tr> <tr><td>24.80</td><td>0.161</td></tr> <tr><td>27.90</td><td>0.212</td></tr> <tr><td>31.000</td><td>0.301</td></tr> </tbody> </table>	Years	LUC of forest to Palm Cultivation	0.000	0.020	3.100	0.030	6.200	0.043	9.300	0.059	12.40	0.074	15.50	0.092	18.60	0.113	21.70	0.133	24.80	0.161	27.90	0.212	31.000	0.301
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27.90	0.212																									
31.000	0.301																									

4.3.2.1 Economic dimension

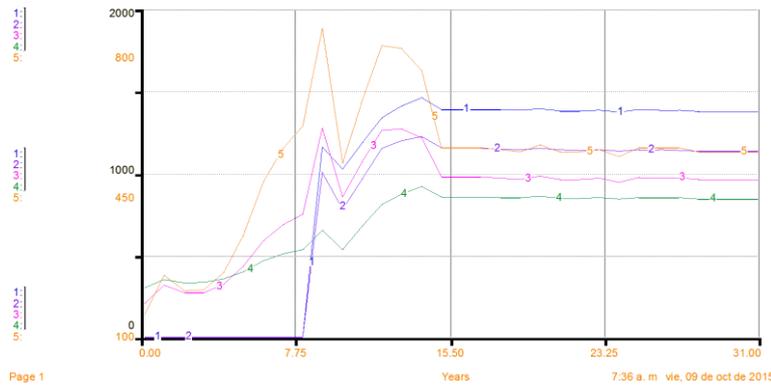
In the pessimistic scenario, biodiesel production will increase to 450,000 t in 2030 (5% of increment), because the blend biodiesel-diesel is maintained in 0.10 during the period of study. A similar trend is observed in biodiesel production capacity, which will raise up to 890,000 t in 2019 and after that the capacity will remain constant. This behavior is a consequence of the reduction of the governmental support. Palm oil production will also fall from 2008 to 2030, because the oil price and the costs linked to biodiesel policy will diminish and the blend biodiesel – diesel will not be incremented. The behavior previously described is shown in Figure 4-44.



1: Palm Oil Production 2: Diesel Consumed in Transport Sector 3: Biodiesel Production
4: Biodiesel Production Capacity 1G 5: Estimated biodiesel consumptions in transport sector

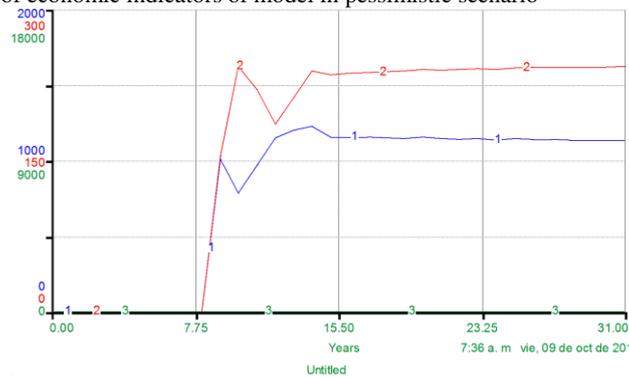
Figure 4-44 Graphical output of economic indicators of model in pessimistic scenario

In Figure 4-45 is observed that under pessimistic conditions, palm oil price, biodiesel price, biodiesel production costs and diesel price will closely follow the oil price trends. These behaviour is expected, because historical data of palm oil price from 1999 to 2008 is correlated to oil price. Furthermore, pessimistic conditions discourage technological improvements, and valorisation of glycerol will not be developed. Then, biodiesel profitability will not be increased as shown in Figure 4-46.



1: Biodiesel Price 2: Biodiesel Production Costs 3: Diesel Price 4: Palm Oil Price 5: Oil Price

Figure 4-45 Graphical output of economic indicators of model in pessimistic scenario

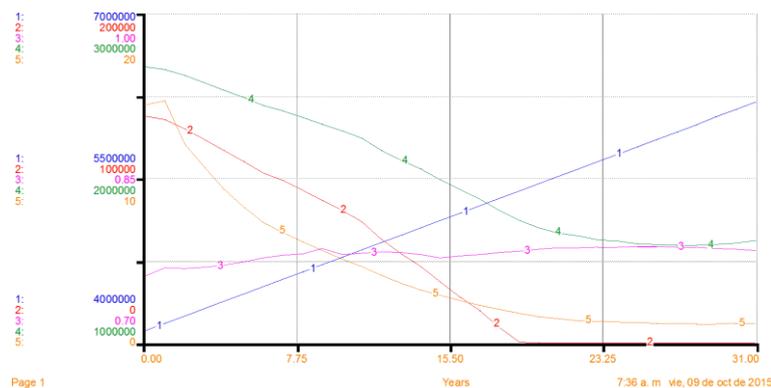


1: Biodiesel Production Costs 2: Profit Biodiesel Production 3: Valorization of glycerol by PDO

Figure 4-46 Graphical output of economic indicators of model in pessimistic scenario

4.3.2.2 Social dimension

Regarding to social indicators, pessimistic conditions influence poor population standards of life, quality of employment and food security. In comparison with baseline scenario, poor population will diminish between 1999 and 2020, but between 2021 and 2030 it will reach a minimum before grow again, as shown in Figure 4-47. In the long term, under the conditions of the pessimistic scenario, poor population will increase in comparison with the baseline conditions. Considering that, in the SD model poor population is correlated to changes in land for palm cultivation which will decrease as shown in Figure 4-48. However, the SD model cannot explain all the complex conditions that influence poor population behavior.

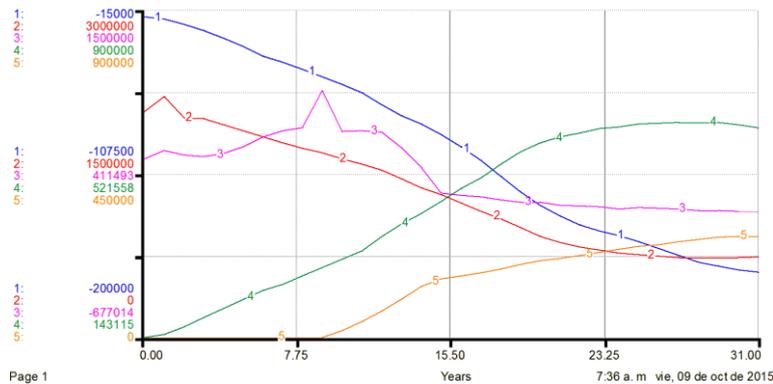


Page 1

1: Population influenced by Palm Cultivation 2: Population Displaced by violence
 3: Land Concentration Index GINI 4: Poor Population 5: Food Security Indicator

Figure 4-47 Graphical output of social indicators of model in pessimistic scenario

About quality of employment in palm-oil cultivation, it will be highly diminished because direct employment will decrease. Agricultural lands will decrease, but from 2024 to 2030 they will reach a steady level, similar to land for palm-oil cultivation in same period as shown in Figure 4-48. That behavior promotes that food security indicator will improve.

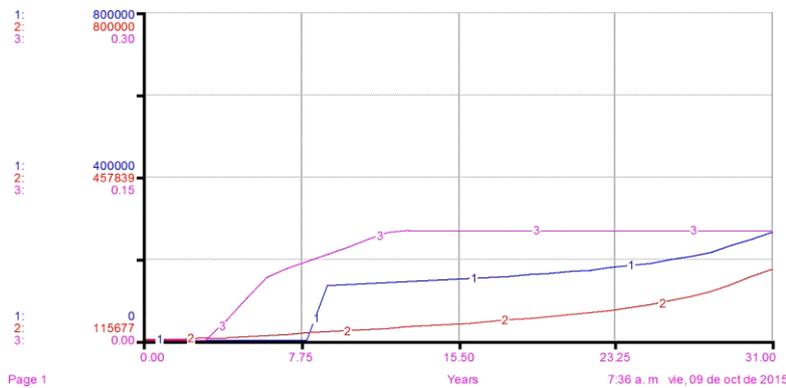


1: Quality of employment in Palm Cultivation 2: Agricultural Land 3: Palm Oil Sales to other uses
 4: Land for Palm Cultivation 5: Land of Palm Cultivation for Biodiesel Production

Figure 4-48 Graphical output of social indicators of model in pessimistic scenario

4.3.2.3 Environmental dimension

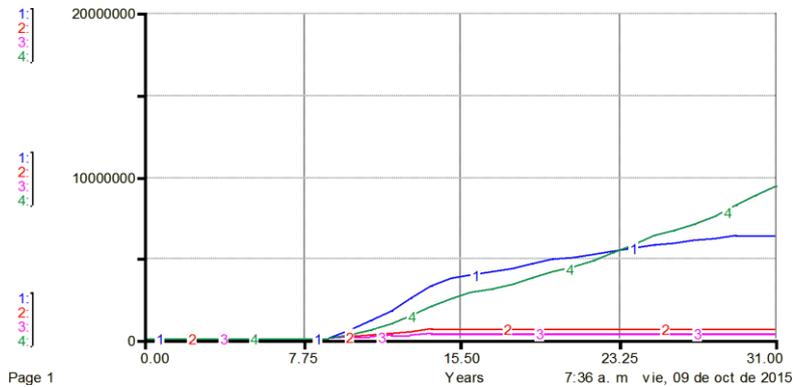
In pessimistic conditions pollutant emissions affecting air quality as a consequence of the use of the biodiesel - diesel blend as biofuel in transportation will diminish as a consequence of the reduction in the number of diesel powered vehicles. Based on pessimistic conditions, pollutant emissions burning diesel will be less than pollutant emission burning biodiesel – blends, as shown in Figure 4-49.



1: Pollutant emission affect quality air: Biodiesel blended
 2: Pollutant emission effect quality air: Diesel 100% 3: Mix Ratio Biodiesel and diesel blended

Figure 4-49 Graphical output of environmental indicators of model in pessimistic scenario

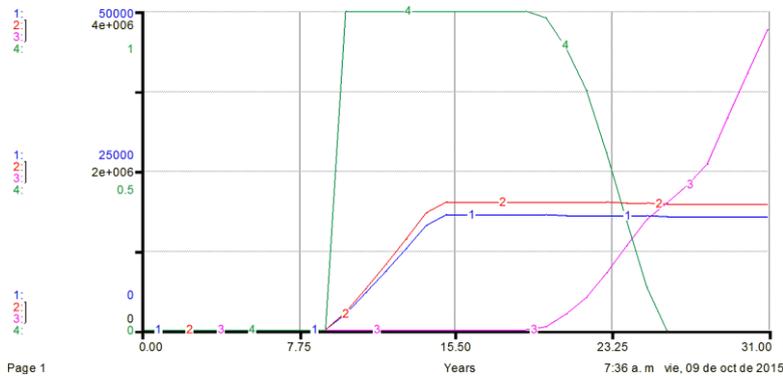
As a consequence, lands for palm cultivation used for biodiesel production, GHG absorption in palm oil cultivation and GHG emission by direct land use change will diminish, as shown in Figure 4-50.



1: GHG Absorption in oil palm cultivation 2: GHG by biodiesel production and supply chain transport
3: GHG by oil palm cultivation and palm oil extraction 4: GHG by direct land use change

Figure 4-50 Graphical output of environmental indicators of model in pessimistic scenario

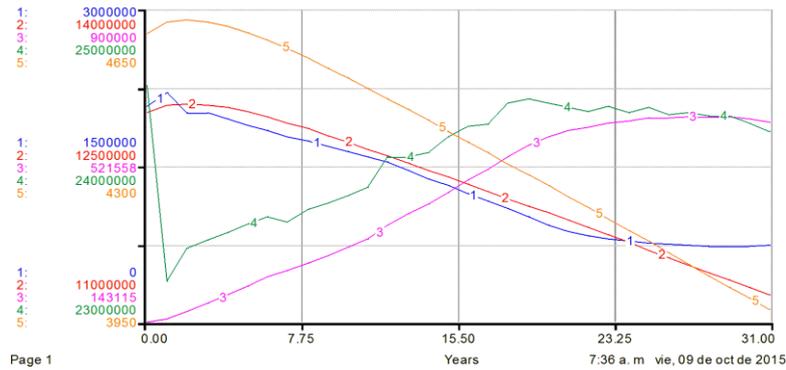
Considering that land use change of forest lands to palm oil cultivation will increase in pessimistic scenario, GHG emission in life cycle of biodiesel production will increase in comparison to baseline conditions, as shown in Figure 4-51. In the same way, the fraction of GHG emissions saving in life cycle of biodiesel will diminish.



1: GHG emissions by indirect land use change 2: GHG emissions if Diesel 100% is used
3: GHG emissions in life cycle of biodiesel 4: Fraction of GHG emission saving by biodiesel-diesel blended

Figure 4-51 Graphical output of environmental indicators of model in pessimistic scenario

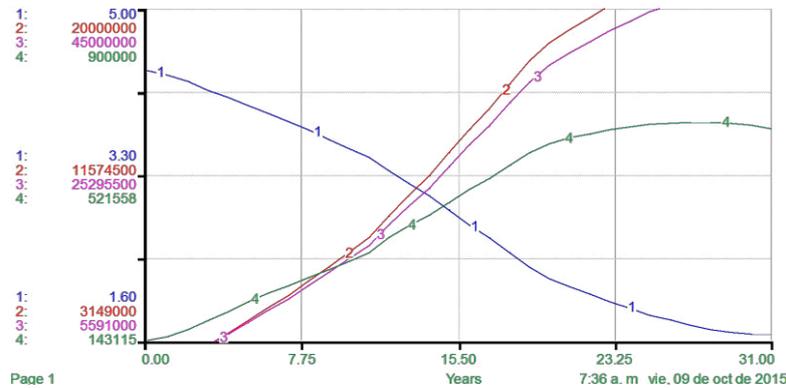
In the long term, as a consequence of higher poor population in pessimistic scenario compared to baseline conditions, livestock lands will diminish in the same period, as shown in Figure 4-52, because in the SD model both indicators are correlated. It is necessary to conduct further research to understand better the relation between poor population and livestock land use change.



1: Agricultural Land 2: Forest and Ecosystems lands 3: Land for Palm Cultivation, 4: Livestock Land 5: Biodiversity Indicator

Figure 4-52 Graphical output of environmental indicators of model in pessimistic scenario

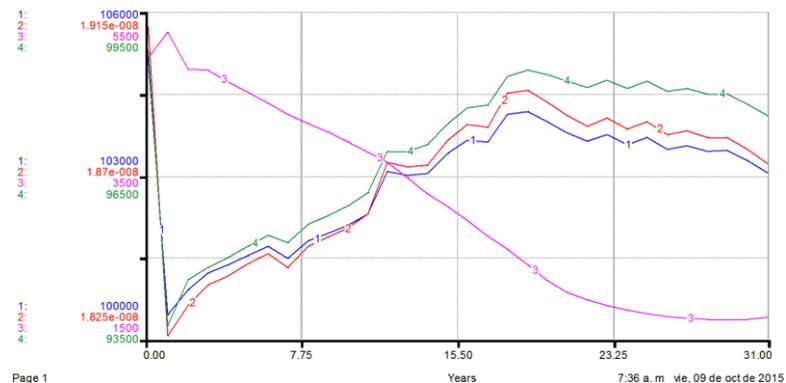
Due to the higher amounts of agrochemical products applied in land for palm cultivation, soil loss will increase too. As a consequence crop yield in palm cultivation will have a critical reduction (4.4 in 1999 to 1.7 in 2030). These behaviors are shown in Figure 4-53.



1: Crop Yield in Oil Palm Cultivation 2: Agrochemical applied in land for Palm Cultivation, 3: Soil Loss in Palm Cultivation 4: Land for Palm Cultivation

Figure 4-53 Graphical output of environmental indicators of model in pessimistic scenario

Water demand will diminish in the pessimistic scenario (Figure 4-54). Water scarcity index will diminish because water demanded by livestock lands will be lower too. Related to energy outputs in biodiesel production, in general, all of them will diminish, due, principally, to crop yield reduction (Figure 4-55).



1: Water Demand in Biodiesel Supply Chain 2: Water Scarcity Index, 3: Agricultural Water Demand 4: Livestock Water Demand

Figure 4-54 Graphical output of environmental indicators of model in pessimistic scenario

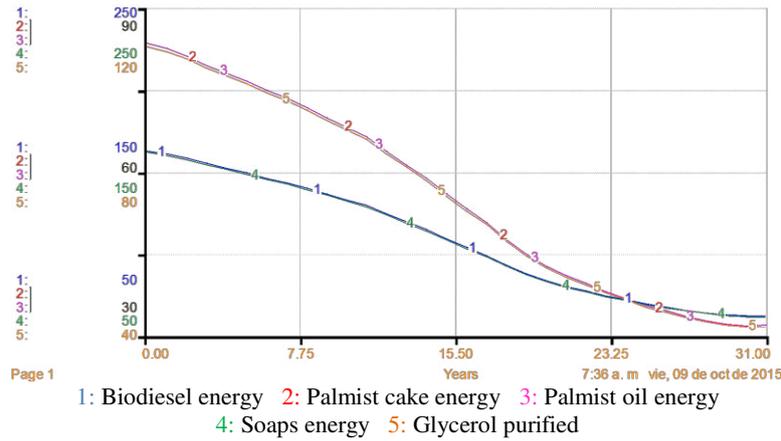


Figure 4-55 Graphical output of environmental indicators of model in pessimistic scenario

4.3.2.4 Political dimension

Pessimistic scenario confirms that if costs linked to biodiesel policy will diminish and the blend biodiesel - diesel is not increased, biodiesel production, palm oil production, biodiesel profitability, the index of energy diversity and GHG emission saving in life cycle of biodiesel will diminish too, as shown in Figure 4-56.

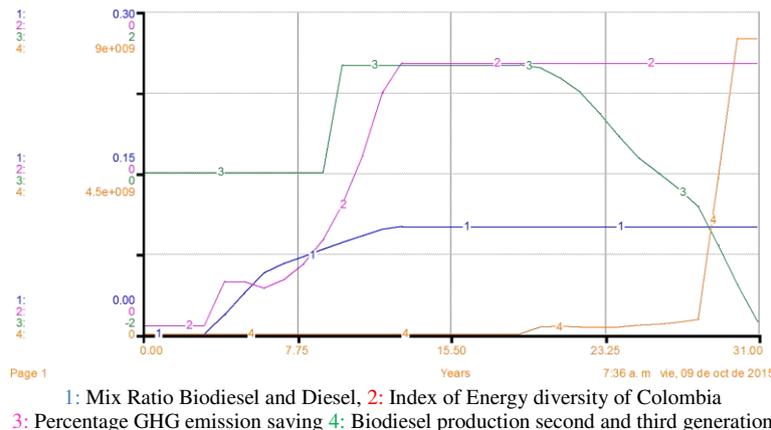
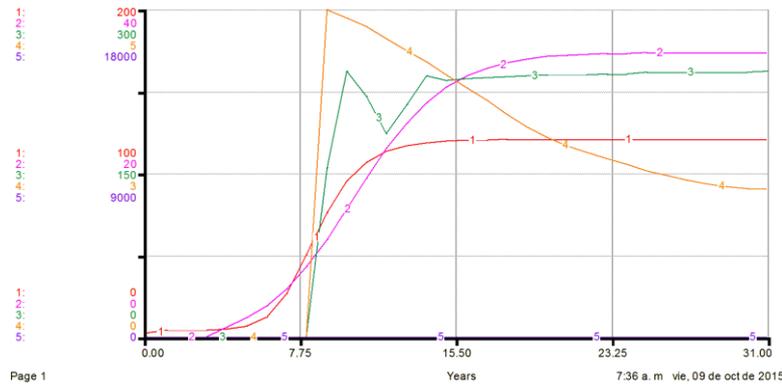


Figure 4-56 Graphical output of politic indicators of model in pessimistic scenario

4.3.2.5 Technological dimension

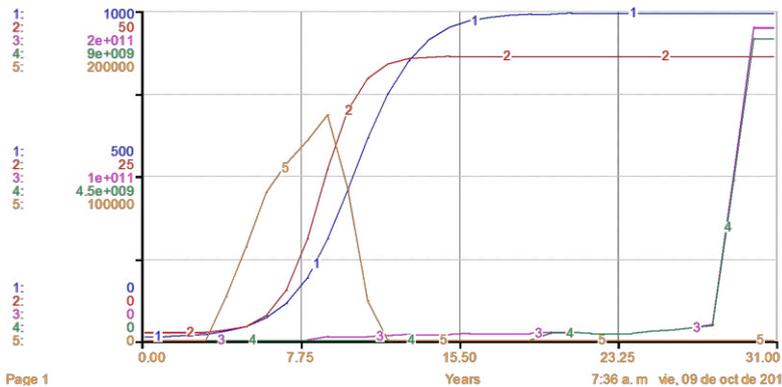
As blend biodiesel – diesel will be kept constant between 2013 and 2030, valorization of glycerol will not be developed, under the SD conditions, and the net energy ratio will diminish, despite the technological maturity, as shown in Figure 4-57.



1: Articles in Journal scientific about Biodiesel production 1G 2: Patents about Biodiesel production 1G
 3: Profit of biodiesel production 4: Net energy ratio 5: Profit of valorization glycerol through PDO

Figure 4-57 Graphical output of technological indicators of model in pessimistic scenario

As biodiesel production will decrease in the pessimistic scenario, unsatisfied demand of biodiesel in transport sector will increase. This unsatisfied demand would be satisfied by diesel or imports. However, technological maturity and international production of second and third generation biodiesel will start up biodiesel production of second and third generation in 2020, as shown in Figure 4-58.



1: Patents about Biodiesel production 2G and 3G 2: Articles in journal scientific about Biodiesel production 2G and 3G
 3: International Production of Biodiesel 2G and 3G 4: Colombian biodiesel production of 2G and 3G
 5: Unsatisfied demand of biodiesel in transport sector

Figure 4-58 Graphical output of technological indicators of model in pessimistic scenario

4.4 Scenario analysis discussion

The scenario analysis is developed with the aim to propose conditions that promotes sustainable biodiesel production in the Colombian context. It is carried out as recommendation for the Colombian government and as an advice in order to make more robust decisions about the management of this system. Conditions and recommendations are described taking into account sustainability assessment framework of principles and criteria proposed in Chapter 2 in each sustainability dimension.

4.4.1 Economic dimension

- Government policy should consider promote the increment of the blend biodiesel - diesel up to 0.25 to 2030. However technical limitations of the engines vehicles should be considered. Biodiesel policy and governmental subsidies should be focused to technological improvement in biodiesel production to increase the process efficiency and the net energy ratio, and to reduce the palm oil consumption and the water demand, and to promote sub products valorization, especially glycerol.

4.4.2 Social dimension

- Oil palm cultivation should be increased. However, it should be done improving the quality of employment, leading to reducing displaced and poor population.
- Land concentration should be diminished with the aim to reduce distribution inequality of land ownership.
- Agricultural lands should be increased due to its positive effect on food security. According to the model prediction, if livestock lands diminish, agricultural lands will increase. However, this behavior could be investigated in further detail.

4.4.3 Environmental dimension

- Technological improvement oil palm cultivation will be conducted. Specially looking for reduce soil loss, water demand and agrochemical use reduction.
- Governmental policies should promote the reduction of forest land use change to oil palm cultivation. This condition has important effects on GHG emission saving in life cycle of biodiesel production.

4.4.4 Political dimension

- Colombian biodiesel policy should promote technological improvement in oil palm cultivation and biodiesel production of first, second and third generation.
- Colombian government should promote strategies to enhance the added value of biodiesel sector. The consequence will be, increase biodiesel profitability through improving process efficiency, reduction biodiesel costs, and valorization of sub-products.

- Private investors need benefits to develop projects to increase biodiesel production capacity. It could be possible if biodiesel profitability increases implementing the strategies previously mentioned. In this way, government support could be progressively reduced.
- Environmental policies should be conducted to minimize forest and ecosystem land use change to, direct and indirect, oil palm cultivation. In this way, policies could promote environmental or GHG emission certifications to access carbon credit market.

4.4.5 Technological dimension

- Technological improvements in biodiesel production to increase process efficiency and by-products valorization, especially glycerol, have an important effect on biodiesel profitability and should be promoted.

Conclusions

In this chapter the SD model was used to establish a baseline scenario. A sensitivity analysis was performed to define the conditions for an optimistic and a pessimistic scenario. Simulation of the baseline scenario provided a consistent description of future biodiesel production in Colombian context. The results obtained enabling to improve the understanding of the complex relations within the biodiesel sector, the through the sustainable indicators that describe it.

It was determined that the SD model is sensitive to exogenous indicators that promote or discourage a sustainable biodiesel production. Among the exogenous indicators is important to mention the oil price, the number of diesel powered vehicles, the costs linked to biodiesel policies, the agrochemicals applied in palm oil cultivation, the biodiesel-diesel blend, the technological efficiency factor and the lands use change.

Baseline simulation, sensitivity analysis and scenario analysis show that there is no single strategy capable of improving the sustainable biodiesel production in the five dimensions. Thus, combined strategies such as government support hand in hand with technological developments, food security, quality of employment increment, and reduction of forest and ecosystem lands use change to palm oil production lands and others discussed in scenario analysis will be promote a sustainable biodiesel production.

The SD model does not take into account all the variables and conditions to be considered in sustainability assessment, due to the scarcity of data linked to a particular indicator. Thus, the

SD model provides an appropriate tool to assess the key indicators that enable to identify conditions and opportunities to improve biodiesel production.

Chapter 5: Conclusions and recommendations

5.1 Conclusions

This study contributes to the sustainability analysis knowledge by proposing a new framework, named Triple Bottom Line Extended (TBL+), to assess biodiesel production. The framework provides a multidimensional point of view, based on five dimensions: social, economic, environmental, political and technological. It is comprised by 13 principles, 40 criteria, and 150 indicators, defined based on literature review. This new framework provides a hierarchical approach to guide bioenergy assessing projects.

Principles and criteria were validated through a new methodology proposed, which permitted the integration of expert consultation, descriptive statistical analysis and data visualization. Expert consultation was conducted based on the following attributes of importance: relevance, ease of measurement and reliability. These were used to grade the impact of each principle and criterion on the assessment framework. A high correlation was identified between ease of measurement and reliability.

The main result of the validation methodology applied was the selection of five dimensions, 13 principles and 31 criteria, recommended to perform the sustainability assessment framework for biodiesel production. Furthermore, data visualization remarks the possibility of evaluating two or more sustainability dimensions through one criterion.

The principles, criteria and indicators of the framework were used to design and implement in Stella ® software a System Dynamics (SD) model. The characteristics, interaction, and influences of the biodiesel production system were displayed in causal loops diagrams (CLD) by each sustainability dimension. After, CLD were mathematically represented using functions and parameters obtained from real data collected in the period 1999 – 2013.

The SD model was applied to predict the behavior in the period 2014 – 2030 for the biodiesel production system in Colombia considering the current conditions (baseline scenario) and conditions that promote (optimistic scenario) and discourage (pessimistic scenario) biodiesel production. To establish the conditions of the optimistic and pessimistic scenarios, the results obtained in the baseline simulation and a sensitivity analysis were used. The sensitivity analysis allowed us to establish which exogenous indicators have the highest affect in the SD model.

Among the exogenous indicators which have a greater influence on sustainability the most important are: oil price, the number of diesel powered vehicles, the costs linked to biodiesel policies, the agrochemicals applied in palm oil cultivation, the biodiesel-diesel blend, the technological efficiency factor and the lands use change.

The scenario analysis process allowed us to generated recommendations for the decision makers and stakeholders to make more robust decisions about the management of the Colombian biodiesel system.

The results suggest that biodiesel policy and governmental subsidies should be focused on:

The increment of processes efficiency and net energy ratio, through technological enhancement of the Colombian biodiesel supply chain.

The reduction of the forest lands use change to oil palm cultivation.

The reduction of palm oil consumption and water demand.

The promotion of by-products valorization, especially glycerol.

The enhancement of food security, quality of employment, technological improving in oil palm cultivation linked to soil conservation and crop yield are recommended.

As a final thought, if biodiesel profitability increases implementing the strategies previously mentioned, government support could be progressively reduced.

5.2 Limitations

The hierarchical sustainability assessment framework of PC&I for biodiesel production proposed in this work has the following limitations:

First, the framework applicability is restricted to renewable energy sources whose raw material is biomass.

Second, for assessing biodiesel production in other specific context, for example in other country, it is necessary to define a new set of indicators for each criterion, and collect new data to set the SD model to the new context.

Third, although the number of experts who validated the framework is significant (62), most of them are immersed in the Latin American context, work for Universities and

their area of expertise is Technological and Environment. Thus, it is important to strength the validation process including experts from other geographical areas, organizations and expertise domains. However, it is important to note that, according to the results of the Principal Component Analysis developed in this work, the grades given by the experts to principles and criteria were not correlated with their geographical origin, type of organization or expertise area.

Regarding to the SD model, this does not take into account all the variables and conditions to be considered in sustainability assessment, due to the scarcity of data linked to particular indicators. Then, the SD model provides an appropriate tool to assess the key indicators that enable to identify conditions and opportunities to improve biodiesel production.

Finally, the scenario analysis conducted in this study is based on academic interest and research questions. The next step will be to propose new scenarios incorporating the points of view of government, community, biodiesel producers and other stakeholders. After that, the results obtained using the SD model can be communicated, diffused and confronted fed by the different actors of the Colombian biodiesel system, making it more robust and closer to the real situation of the system.

5.3 Recommendations

The new proposed framework implies that a hierarchical approach can provide the necessary guidance for understanding and assessing the biodiesel production system. This work strengthens sustainability assessments using a multidimensional view biodiesel including social, economic, environmental, political and technological. Furthermore this work contributes to methodological tools to validate the assessment framework, integrating expert consultation with descriptive statistical analysis and data visualization.

The sustainability assessment for other kind of biofuels can be started with the definition of a sustainability assessment framework based on the PC&I proposed in chapter 2. After that, it is possible to conduct an expert validation involving community consultation. Later, it is possible to define to design and implement the SD model, following the methodology presented in Chapter 3.

Regarding to the methodological approach used in this work, it can be generalized to another bioenergy sources and can be summarized in the following steps:

- To define a hierarchical framework of sustainability assessment that integrates principles, criteria and indicators of sustainability based on literature review, expert consultation and community sounding.
- To define causals loops diagrams by each sustainability dimension to visualize interrelationships of the principles, criteria, and indicator.
- To convert causals loops into quantitative model, called the stock and flow diagram.
- To validate a quantitative model in specific context
- To identify the indicators to carry out a sensitivity analysis and to define the conditions those promote or discourage a sustainable biofuel production in a time horizon.

This work is a starting point to assess the sustainability of biodiesel production, because several aspects and conditions can be further considered if the historical data were available:

- Promotion of commitment to ethics and transparency and compliance with local laws
- Influence of engine trends in diesel powered vehicles.
- Influence second and third generation biodiesel production first generation biodiesel production, land use change, soil and water quality, and GHG emission saving in life cycle.
- Influence of national capability in biodiesel research.
- Perform another sensitivity and scenario analysis on other exogenous indicators to know the SD response.
- Incorporate sustainable conditions relevant to different stakeholders in biodiesel system.

With the aim to strengthen the SD model, it is important to conduct investigations to clarify the agricultural lands trends, and its relations with livestock lands, poor population, and other population dynamics, as well as some employment conditions, for example the affiliation of the employees to occupational health system. It would be interesting to analyze the influence of costs linked to employment on biodiesel profitability, especially during palm oil cultivation. In the economic dimension, the Colombian government will be interesting to analyze the influence of some community organizations and workers unions on the growing of biodiesel production.

In technological dimension would be interesting to conduct a study about technological substitution in biodiesel production, influence of non-edible raw materials, process intensification, and strategies of technological transfer of scientific research to industrial application.

The environmental indicators used in this work should be discussed with governmental institutions related to, considering the lack of data information, especially about biodiversity and water supply and quality, in areas influenced by palm cultivation. The SD model provides a starting point of a future model for analyze synergistic and cumulative environmental impacts, to medium and long term.

In the SD model a new innovative indicator was proposed related to biodiversity, quality of employment, factor promotion of biodiesel production of second and third generation, among others. This indicator can be studied in more detail with the aim to propose sustainability indices in each dimension or interdimensional.

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Appendix

Appendix 1. Document linked to principles, criteria and indicator.

SOCIAL DIMENSION OF SUSTAINABILITY		References
Biomass growers and biodiesel processing companies must:		
PRINCIPLE 1: Respect property rights, land tenure and customary and traditional rights		
CRITERION 1: Respect the rights of land access and land tenure for peasant and indigenous communities.	INDICATOR 1. Indigenous peoples shall control biodiesel management on their lands and territories unless they delegate control with free and informed consent to other agencies.	Edgard Gnansounou, 2011 Vaccaro et al. 2010 Buchholz, Luzadis, et Volk 2009 FSC, Forest Stewardship Council GBEP, Global Bioenergy Partnership SAN/RA, Sustainable Agriculture Network/Rain forest Alliance Interamerican Development Bank- Sustainability Scorecard PEFC, Program for the Endorsement of Forest Certification schemes RTRS, Roundtable for Responsible Soy Production Nordic Ecolabelling of Fuels RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union
	INDICATOR 2. Biodiesel management shall not threaten or diminish, directly or indirectly, either the resources or tenure rights of indigenous peoples.	
INDICATOR 3. Sites of special cultural, ecological, economic or religious significance to indigenous peoples shall be clearly identified in cooperation with such peoples, and recognized and protected by biodiesel managers.		
CRITERION 2: Promote the minimization of conflicts over the use, access and land tenure.	INDICATOR 4. Promotion of the involvement of stakeholders about use of land, management of conflicts and tenure of land.	
	INDICATOR 5. Avoidance of land tenure conflicts.	
	INDICATOR 6. Projects should not exclude poor people from the land in order to avoid leakage effects.	
	INDICATOR 7. Land ownership should be equitable.	
	INDICATOR 8. Number of rights granted by constitutions, regulations and official tribunals or other laws: customary, casual, temporary and secondary.	
	INDICATOR 9. Number of people in a population with safe titles (for example, registered) in relation to the number of people with insecure titles on the land, in the area of direct influence of the plantations of palm oil and biodiesel processing.	
Biodiesel supply chain must:		
PRINCIPLE 2: Be socially acceptable		
CRITERION 3: contribute to national energy security and the access of rural communities to energy. CRITERION 4: To prevent generation of environmental noise. CRITERION 5: To prevent changes in landscape generating undesirable visual impact for communities.	INDICATOR 10. Index of energy matrix diversification.	(Musango et al. 2011) (Amigun, Musango, et Brent 2011) (Musango et al. 2012) (Edgard Gnansounou 2011) (Markevicius et al. 2010) (Kurka et Blackwood 2013) FSC, Forest Stewardship Council SAI, Social Accountability International IFOAM, International Federation of Organic Agriculture Movements RTRS, Roundtable for Responsible Soy Production UNEP, 2009. Towards Sustainable Production RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RTFO, Renewable Transport Fuel Obligation – UK Social Fuel seal – Brazil
	INDICATOR 11. Government Investment in electricity infrastructure.	
INDICATOR 12. Qualitative indicator scale of 1 to 5, 1 being the lower noise impact and 5, a significant noise impact.		
INDICATOR 13. Qualitative indicator scale of 1 to 5, 1 being the lower visual impact and 5, a significant visual impact.		
CRITERION 6: To contribute to local prosperity associated with the reduction of poverty and the promotion of human rights.	INDICATOR 14. Stakeholder involvement in the decisions that concern them	
	INDICATOR 15. Total annual national of households without access to public services of the total number of families, in the direct area influence of oil palm plantations and mining and transformation plants of biodiesel	
	INDICATOR 16. Access to health care and medication	
	INDICATOR 17. Total annual national of Illiteracy people aged 15 or more of the total number of persons, in the direct influence of oil palm plantations and mining and transformation plants of biodiesel.	
	INDICATOR 18. Opportunities for employment: Total annual number of employment in plantation of biomass, extraction and transformation plant.	
	INDICATOR 19. Total annual national of head of household's opinion about better living standards of their home, which was about 5 years ago of the total number of families, in the direct area influence of oil palm plantations and mining and processing plants of biodiesel.	
	INDICATOR 20. Unsatisfied basic needs: Weighted average of the annual percentages of people in poverty, according to the indicator of unmet basic needs in the municipalities that are part of the zone of influence of the biodiesel production system.	
	INDICATOR 21. Number of organizations of the community partition in biodiesel production system per year.	
	INDICATOR 22. Participation of small farmers (less than 20 ha): Number of small farmers of palm oil for biodiesel per number total farmers of palm oil for biodiesel.	
	INDICATOR 23. Land prices of a hectare of land with palm oil for biodiesel in areas influenced by the production of biodiesel per year.	

SOCIAL DIMENSION OF SUSTAINABILITY		References
	<p>INDICATOR 24. Total national of people displacement from areas affected by the number of persons received by displacement from other areas in the direct influence of oil palm plantations and mining and processing plants of biodiesel.</p> <p>INDICATOR 25. Total national estimated annual lands usurped hectares in areas of direct influence of the biodiesel production system.</p> <p>INDICATOR 26. Annual amount of conflict associated with guerrilla groups, drug trafficking, or common criminals who present in the direct influence of oil palm plantations and mining and processing plants of biodiesel.</p>	
Biodiesel supply chain must:		
PRINCIPLE 3: Promote responsible work conditions through all their activities		
CRITERION 7: ensure that all their activities are carried out protecting health and promoting safety for employees.	INDICATOR 27. The Process Route Healthiness Index (PRHI)	(Halog et Manik 2011) Edgard Gnsounou 2011) (Buchholz, Luzadis, et Volk 2009) NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. ACCS, Assured Combinable Crops Scheme SAI, Social Accountability International Sustainability Guide in Biomass Production and Processing in the Biofuel chain in Colombia ISO 26000 – Responsibility social. GBEP, Global Bioenergy Partnership ISCC, International Sustainability and Carbon Certification SAN/RA, Sustainable Agriculture Network/Rain forest Alliance Bonsucro, Better Sugarcane Initiative FLO, Fairtrade Labelling Organizations International PEFC, Program for the Endorsement of Forest Certification schemes RTRS, Roundtable for Responsible Soy Production RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RFS2, Renewable Fuel Standard, the United States,2010 RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union LCFS, Low Carbon Fuel Standard (LCFS), California, United States. Interamerican Development Bank- Sustainability Scorecard
	INDICATOR 28. Affiliation of the employees to occupational hazards insurance	
	INDICATOR 29. Hazardous Materials Protection: Employer provides and employees use adequate protective clothing, appropriate safety equipment, and filtered air respirator systems and/or positive pressure cabs for workers handling highly toxic chemicals.	
	INDICATOR 30. Number of work accidents and occupational sicknesses in the different stages of the biodiesel production system	
	INDICATOR 31. Sanitation: Employer provides clean drinking water and clean latrines with hand-washing stations to workers.	
	INDICATOR 32. Insurance against workplace injury: Employer provides workers compensation and disability insurance for all full time employees.	
	INDICATOR 33. Environmental training of employees, Job instructions, on the job training	
INDICATOR 34. Fair Treatment of Workers		
CRITERION 8: To guarantee the respect of labor laws (associated with forced child labor, discrimination, disciplinary practices, working hours, salaries, incidence of occupational accidents, illnesses and deaths, forced and compulsory labor, and unions).	INDICATOR 35. Number of workers with direct labor contracts with enterprises	
	INDICATOR 36. Number of workers employed through other forms of recruitment (associations, intermediary companies).	
	INDICATOR 37. Number of workers who belong to trade unions	
	INDICATOR 38. Number of workers under 18 years of age	
Biomass cultivation and production of biodiesel must:		
PRINCIPLE 4: Prevent alteration to food supply or other local uses of biomass (e.g. energy production, as medicine raw material and as building material)		
CRITERION 9: To prevent alteration to trade and food supply at the local level.	INDICATOR 39. The consumer price index (CPI) measures changes over time in the general level of prices of consumer goods and services that households acquire, use or pay for consumption.	FAO 2012) (Oviedo et al. 2011) (Timilsina et Shrestha 2011) (Pruyt et Sitter 2008) (Buchholz, Luzadis, et Volk 2009) (Markevicius et al. 2010) (Kurka et Blackwood 2013) GBEP, Global Bioenergy Partnership Interamerican Development Bank- Sustainability Scorecard NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. GAP, Global Partnership for Good Agricultural Practice IFOAM, International
	INDICATOR 40. Undernourishment: Proportion of undernourished in the population (%). Annual number of undernourished people in the total population of the country	
	INDICATOR 41. Amount of hectare of agricultural land and Livestock Research in active production relative to total land available with this vocation, per year.	
	INDICATOR 42. Vulnerability Analysis and Mapping VAM, is network of food security experts who work closely with national governments, UN partners and NGOs to inform food insecurity and hunger related programs and policies.	
CRITERION 10: To prevent alteration to biomass production for traditional local uses other than biodiesel (e.g. energy production, as medicine raw material and as building material).		Federation of Organic Agriculture Movements Sustainability Guide in Biomass Production and Processing in the Biofuel chain in Colombia RTRS, Roundtable for Responsible Soy Production UNCTAD Biofuels Initiative RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil RTFO, Renewable Transport Fuel Obligation – UK Social Fuel seal – Brazil Directive 2009/28/EC of the European Union Food security information network. http://www.fsincop.net/resource-centre/detail/en/c/178639/

POLITICAL DIMENSION OF SUSTAINABILITY		References
PRINCIPLE 5: National promotion policies for the production and consumption of first generation biodiesel must be in accordance with international policies.		
CRITERION 11: Level of agreement between the amount of biodiesel produced domestically under a subsidy scheme and the one produced internationally under similar schemes.	INDICATOR 43. Amount of USD incentive or tax in previous year less the incentive or tax in the current year with relationship the incentive or tax in the current year	(Musango et al. 2012) (Edgard Gnansounou 2011) (Vaccaro et al. 2010) (Franco et Flórez 2009) (Timilsina et Shrestha 2011) (Bantz et Deaton 2006) (Zapata, Franco, et Dwyer 2011) (Markevicius et al. 2010) (Kurka et Blackwood 2013)
CRITERION 12: Level of agreement between domestic “1 st -gen./advanced” biodiesel production ratio.	INDICATOR 44. Local price in USD of biodiesel in a scheme of biofuel price controls.	
CRITERION 13: Level of agreement between the percentages of national biodiesel blend – diesel and percentages of international blend.	INDICATOR 45. (production of first generation biodiesel)/(production of advanced biodiesel) and international “1 st -gen./advanced” ratios	
CRITERION 14: Level of national capability in biodiesel research and development (first generation and advanced) regarding international capabilities.	INDICATOR 46. The percentages of national biodiesel blend – diesel and percentages of international blend.	
	INDICATOR 47. Fiscal costs of the implementation of the biodiesel promotion policy	
	INDICATOR 48. Research and development expenditure (% of GDP)	
PRINCIPLE 6. National policies related to the promotion of biodiesel production should be consistent with international environmental policies on acceptable forms of biomass, suitable land for the cultivation of biomass and allowed thresholds of greenhouse gas emissions in the life cycle of biodiesel		
CRITERION 15: Amount of biomass produced domestically in compliance with international standards (type of biomass that does not compete with food).	INDICATOR 49. Annual amount of raw material for the production of biodiesel produced compliance with the criteria of renewable biomass	FSC, Forest Stewardship Council NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. Sustainability Guide in Biomass Production and Processing in the Biofuel chain in Colombia ISO 26000 – Responsibility social. ISCC, International Sustainability and Carbon Certification Interamerican Development Bank- Sustainability Scorecard PEFC, Program for the Endorsement of Forest Certification schemes RTRS, Roundtable for Responsible Soy Production RFS2 United States (Epa 2010) BLE, Sustainable Biomass Production. Germany RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil Directive 2009/28/EC of the European Union FLO, Fairtrade Labelling Organizations International
CRITERION 16: National amount of land used for growing biomass for biodiesel production that meets the international requirements of land suitable for use (i.e. those that do not come from direct exchange of primary forests, exclusion areas with high biodiversity value, land with high carbon stocks and ecologically sensitive areas declared as protected).	INDICATOR 50. Amount of biodiesel produced under voluntary certification criteria (e.g. RSPO, ISCC, NTA 8080) relative to the total amount of biodiesel produced globally.	
CRITERION 17: Amount of domestically produced biodiesel that meets international policy on minimum average or threshold of greenhouse gas emissions in their life cycle, including indirect changes in land use.	INDICATOR 51. Total global consumed tons of 1 st generation biodiesel that are permitted by international policies	
PRINCIPLE 7. The actors involved in biodiesel’s production chain should promote commitment to ethics, transparency and compliance with local laws		
CRITERION 18: Level of perception of the local community about the degree of ethical commitment by the actors in biodiesel’s production chain.	INDICATOR 52. Define and communicate the standards of ethical behavior in the organization	RTRS, Roundtable for Responsible Soy Production RFS2 United States (Epa 2010) BLE, Sustainable Biomass Production. Germany RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation LCFS, Low Carbon Fuel Standard (LCFS), California, United States.
	INDICATOR 54. Reporte de multas por incumplimiento legal en temas laborales, impuestos, ambientales, entre otros.	
	INDICATOR 55. Awareness of responsibilities, according to applicable laws (environmental, fiscal, social and labor) can be demonstrated.	
	INDICATOR 56. Adopt and implement the standards of ethical behavior. Establish mechanisms for monitoring and verification.	
CRITERION 19: Level of perception of the local community about the commitment to transparency and compliance with local laws by the actors involved in biodiesel’s production chain.	INDICATOR 57. The organization must be transparent in its activities, which makes control over them, how to be making the decisions, and how their functions are defined.	
	INDICATOR 58. The organization must be clear about the source of funds for their activities	
	INDICATOR 59. The organization must know the likely effects of their decisions on stakeholders, society, economy and environment.	
	INDICATOR 60. The organization inform to consumers about the environmental effects of products they are consuming and to raise environmental standards in the manufacturing of specific products	
	INDICATOR 61. Production of any Genetically Modified Organisms must comply with legal requirements.	

ECONOMIC DIMENSION OF SUSTAINABILITY		References
PRINCIPLE 8. Biodiesel production must be sustainable at both macroeconomic and microeconomic level		FSC, Forest Stewardship Council UNCTAD Biofuels Initiative
CRITERION 20: Level of influence (international and domestic) of reserves, production, consumption and prices for oil on the production of first generation biodiesel.	INDICATOR 62. Global Petroleum reserves per year and per global tons of first generation biodiesel produced	(Oviedo et al. 2011)
	INDICATOR 63. Global Petroleum production per year and biodiesel per global tons of first generation biodiesel produced	
	INDICATOR 64. Global annual Petroleum consumption per global tons of first generation biodiesel produced	
	INDICATOR 65. Global annual Prices of petroleum per global tons of first generation biodiesel produced	
	INDICATOR 66. Local annual Petroleum reserves per local tons of first generation biodiesel produced	
	INDICATOR 67. Local annual Petroleum production per local tons of first generation biodiesel produced	
	INDICATOR 68. Local annual Petroleum consumption per local tons of first generation biodiesel produced	
	INDICATOR 69. Local annual Prices of petroleum per local tons of first generation biodiesel produced	
	INDICATOR 70. Global annual production quantity of diesel per global tons of first generation biodiesel produced	
INDICATOR 71. Global annual consumption quantity of diesel per global tons of first generation biodiesel produced		
INDICATOR 72. Global annual prices of diesel per global tons of first generation biodiesel produced		
INDICATOR 73. Local annual production quantity of diesel per local tons of first generation biodiesel produced		
INDICATOR 74. Local annual consumption quantity of diesel per local tons of first generation biodiesel produced		
INDICATOR 75. Local annual prices of diesel per local ton of first generation biodiesel produced		
INDICATOR 76. Local annual quantity of Vehicle diesel per local tons of first generation biodiesel produced		
CRITERION 22: Annual production (international and domestic) of first generation biodiesel.	INDICATOR 77. Global annual production quantity of biodiesel 1 ^a generation	(Musango et al. 2011) (Musango et al. 2012) (Edgard Gnansounou 2011) (Wang, Calderon, et Lu 2011) (Oviedo et al. 2011) (Franco et Flórez 2009) (Timilsina et Shrestha 2011) (Bantz et Deaton 2006) (Wang, Calderon, et Lu 2011) (Zapata, Franco, et Dynner 2011) (Kurka et Blackwood 2013)
	INDICATOR 78. Global annual consumption quantity of biodiesel 1 ^a generation per global tons of first generation biodiesel produced	
	INDICATOR 79. Global annual prices of biodiesel 1 ^a generation per global tons of first generation biodiesel produced	
	INDICATOR 80. Local annual production quantity of biodiesel 1 ^a generation	
	INDICATOR 81. Local annual consumption quantity of biodiesel 1 ^a generation per local tons of first generation biodiesel produced	
	INDICATOR 82. Local annual prices of biodiesel 1 ^a generation per local tons of first generation biodiesel produced	
	INDICATOR 83. Local production capacity of the 1 ^a generation biodiesel per local tons of first generation biodiesel produced	
	INDICATOR 84. Local profitability of production of biodiesel 1 ^a generation per local tons of first generation biodiesel produced	
	INDICATOR 85. Annual balance energy costs in the biodiesel production per local tons of first generation biodiesel produced	
	INDICATOR 86. Annual operational and pollution control cost in the biodiesel production per local tons of first generation biodiesel produced	
	INDICATOR 87. Global annual prices of palm oil per global tons of first generation biodiesel produced	
INDICATOR 88. Global total annual production of palm oil per global tons of first generation biodiesel produced		
INDICATOR 89. Global annual consumption for palm oil for production of biodiesel per global tons of first generation biodiesel produced		
INDICATOR 90. Global annual consumption for palm oil in different uses to biodiesel per global tons of first generation biodiesel produced		
INDICATOR 91. Local annual prices of palm oil per local tons of first generation biodiesel produced		
INDICATOR 92. Local total annual production of palm oil per local tons of first generation biodiesel produced		
INDICATOR 93. Local annual consumption for palm oil for production of biodiesel per local tons of first generation biodiesel produced		
INDICATOR 94. Local annual consumption for palm oil for human consumption per local tons of first generation biodiesel produced		
INDICATOR 95. Aboveground net primary productivity (at the stage of cultivation of oil palm) biodiesel per annual local tons of first generation biodiesel produced. Taking into account the effects of climate change		
INDICATOR 96. Local annual price of byproduct glycerol per local tons of first generation biodiesel produced	INDICATOR 97. Local annual production of byproduct glycerol biodiesel per local tons of first generation biodiesel produced INDICATOR 98. Local annual consumption of byproduct glycerol biodiesel per local tons of first generation biodiesel produced.	
INDICATOR 97. Local annual production of byproduct glycerol biodiesel per local tons of first generation biodiesel produced		
INDICATOR 98. Local annual consumption of byproduct glycerol biodiesel per local tons of first generation biodiesel produced.		
CRITERION 24: Level of influence of production, consumption and prices (international and domestic) for glycerol on the production of first generation biodiesel.	INDICATOR 98. Global annual prices of advanced biodiesel per global tons of first generation biodiesel produced	(Kurka et Blackwood 2013) UNCTAD Biofuels Initiative
	INDICATOR 99. Global annual production of advanced biodiesel per global tons of first generation biodiesel produced	
	INDICATOR 100. Global annual consumption of advanced biodiesel per global tons of first generation biodiesel produced	
CRITERION 25: Level of influence of production, consumption and prices (international and domestic) for advanced biodiesel on first generation biodiesel.	INDICATOR 98. Global annual prices of advanced biodiesel per global tons of first generation biodiesel produced	(Kurka et Blackwood 2013) UNCTAD Biofuels Initiative
	INDICATOR 99. Global annual production of advanced biodiesel per global tons of first generation biodiesel produced	
TECHNOLOGICAL DIMENSION OF SUSTAINABILITY		References
PRINCIPLE 9. Technology used in the biodiesel supply chain should promote the reduction of negative impacts on the environment, efficiency and cost reduction in processes over time		
	INDICATOR 101. Amount of hectares of land required for the production of raw materials for advanced biodiesel or second and third generation.	(Musango et Brent 2011) (Brent et Musango 2013)

TECHNOLOGICAL DIMENSION OF SUSTAINABILITY		References
CRITERION 26: Level of influence of production (international and domestic) of advanced biodiesel from non-edible feedstock on demand (international and domestic) of soil and water resources.	INDICATOR 103. Amount of water required for the production of raw materials and advanced biodiesel or second and third generation transformation.	(Vaccaro et al. 2010) (Timilsina et Shrestha 2011) (Bantz et Deaton 2006) (Kurka et Blackwood 2013) GBEP, Global Bioenergy Partnership UNCTAD Biofuels Initiative UNEP, 2009. Towards Sustainable Production RSB, Roundtable on Sustainable Biofuels
CRITERION 27: Level of influence of global and domestic production of advanced biodiesel based on non-conventional technologies on efficiency of processes and cost reduction.	INDICATOR 104. Reduction of production costs dependent on the production of advanced biodiesel technology apprenticeship	
CRITERION 28: Level of influence of technology trends for engines on the production of first generation biodiesel.	INDICATOR 105. Demand for biodiesel according to the number of vehicles that do not use liquid fuels.	
CRITERION 29. Level of influence of technological learning (global and domestic) in the production of first generation biodiesel on reducing costs over time	INDICATOR 106. Reducing costs of production by independent of production technological learning (associated with technological maturity that can be assessed indirectly by scientific articles and patents advanced biodiesel or second and third generation)	

ENVIRONMENTAL DIMENSION OF SUSTAINABILITY		References
The actors involved in the biodiesel supply chain must:		
PRINCIPLE 10. Ensure their activities maintain or improve the air, soil and water quality, as well as they do a proper management of solid waste and wastewater		
CRITERION 30: To ensure that <u>air quality</u> is maintained or improved.	INDICATOR 107. Annual tons of nitrogen oxide gas emissions engine transport vehicles using biodiesel fuel blends (in the national capital).	(Edgard Gnansounou 2011) (Timilsina et Shrestha 2011) (McBride et al. 2011) (Kurka et Blackwood 2013) ISO 14040 – Life Cycle Assessment GBEP, Global Bioenergy Partnership LCFS, Low Carbon Fuel Standard (LCFS), California, United States. ISO 26000 – Responsibility social. Bonsucro, Better Sugarcane Initiative
	INDICATOR 108. Annual tons of particulate matter gas emissions engine transport vehicles using biodiesel fuel blends (in the national capital)	
	INDICATOR 109. Annual tons of carbon monoxide gas emissions engine transport vehicles using biodiesel fuel blends (in the national capital)	
	INDICATOR 110. Annual tons of total hydrocarbons gas emissions engine transport vehicles using biodiesel fuel blends (in the national capital)	
	INDICATOR 111. Annual tons of total atmospheric acidification burden per unit mass, environmental burden is kg Sulphur dioxide equivalent product (in the national capital)	
	INDICATOR 112. Annual tons of total of persistent organic pollutants (POPs) and substances that deplete the ozone layer (in the national capital)	
CRITERION 31: To promote the <u>efficient use of water</u> to minimize pressure on the local availability of the resource.	INDICATOR 113. Average cubic meters of water available per year in direct area of influence of biodiesel production system (taking into account the effects of climate change)	(BID et MMEC 2012) (FAO 2012) (Musango et al. 2011) (Edgard Gnansounou 2011) (Kurka et Blackwood 2013) CSBP, Council on Sustainable Biomass Production, the United States. ISO 14040 – Life Cycle Assessment GBEP, Global Bioenergy Partnership SAN/RA, Sustainable Agriculture Network/Rain forest Alliance Interamerican Development Bank- Sustainability Scorecard Bonsucro, Better Sugarcane Initiative RTRS, Roundtable for Responsible Soy Production GGLS2, Green Gold Label 2.
	INDICATOR 114. Index linking shortage of water available (m3) with respect to water consumption (m3) in direct area of influence of biodiesel production system	
	INDICATOR 115. Water used in m3 by hectare of palm oil cultivation for biodiesel per year	
	INDICATOR 116. Water used annually in m3 for production of one tons of biodiesel in the step of transformation with in productive chain.	
	INDICATOR 117. Annual quantity of water utilized or recycled of the total water utilized in the biodiesel production.	
	INDICATOR 118. Annual ratio of the amount (m3) of water used for growing biomass and biodiesel production of all water used for human consumption and food crops in the area of direct influence (taking into account the effects of climate change)	
CRITERION 32: To minimize the generation of contaminated effluents and treat such effluents in order to maintain or improve the <u>local water quality</u>	INDICATOR 119. Concentration annual average (mg/l) of suspended sediment in the principal stream (those that are used for human consumption) that are part of the direct influence area (watershed) of oil palm plantations.	(BID et MMEC 2012) (Edgard Gnansounou 2011) (Kurka et Blackwood 2013) NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. ISO 14040 – Life Cycle Assessment GBEP, Global Bioenergy Partnership
	INDICATOR 120. Concentration annual average (mg/l) of phosphorus (P) in the principal stream (those that are used for human consumption) that are part of the direct influence area (watershed) of oil palm plantations, as annual average.	
	INDICATOR 121. Concentration annual average (mg/l) of nitrogen in the principal stream (those that are used for human consumption) that are part of the direct influence area (watershed) of oil palm plantations.	
		Agriculture Source Criteria Nordic Ecolabelling of Fuels UNEP, 2009. Towards Sustainable Production RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation BioNa Dv, Biomass Sustainability order, Germany
		Agriculture Source Criteria Nordic Ecolabelling of Fuels UNEP, 2009. Towards Sustainable Production RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union
		GGLS2, Green Gold Label 2. Agriculture Source Criteria Nordic Ecolabelling of Fuels UNEP, 2009. Towards Sustainable Production RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union

ENVIRONMENTAL DIMENSION OF SUSTAINABILITY		References
	INDICATOR 122. Concentration annual average (mg/l) of herbicide concentration in the principal stream (those that are used for human consumption) that are part of the direct influence area (watershed) of oil palm plantations.	ISCC, International Sustainability and Carbon Certification SAN/RA, Sustainable Agriculture Network/Rain forest Alliance Interamerican Development Bank-Sustainability Scorecard RTRS, Roundtable for Responsible Soy Production
	INDICATOR 123. Discharge rate (m ³ /year) of wastewater generated in the production of one tons of biodiesel in transformation industry per year	
	INDICATOR 124. Discharge in kg of nitrate per fresh fruit bunch in oil plantation biodiesel per year	
	INDICATOR 125. Discharge in kg of phosphorus per fresh fruit bunch in oil plantation biodiesel by year	
CRITERION 33: To ensure that <u>non-hazardous and hazardous wastes</u> are managed responsibly (collection, storage, transportation, treatment and/or disposal) by promoting their minimization, reuse and/or recycling.	INDICATOR 126. Amount in tons of hazardous waste taken to a proper final disposal of all waste generated in the stages of cultivation, oil extraction and transformation into biodiesel per year.	(BID et MMEC 2012) (Buchholz, Luzadis, et Volk 2009) FSC, Forest Stewardship Council NTA 8080, Sustainable Production of Biomass—The Netherlands GAP, Global Partnership for Good Agricultural Practice IFOAM, International Federation of Organic Agriculture Movements Sustainability Guide in Biomass Production and Processing in the Biofuel chain in Colombia ISO 14040 – Life Cycle Assessment ISCC, International Sustainability and Carbon Certification SAN/RA, Sustainable Agriculture Network/Rain forest Alliance Interamerican Development Bank-Sustainability Scorecard
	INDICATOR 127. Amount in tons of waste are reuse or recycle with relation of total waste generated in the stages of cultivation of palm oil per year.	
	INDICATOR 128. Amount in tons of waste are recovered or valued with relation of total waste generated in the stages of transformation of palm oil to biodiesel	
	INDICATOR 129. Total amount of non-hazardous waste generated annually per tons of biodiesel produced	
CRITERION 34: The biomass cultivation activities for biodiesel must maintain or improve the <u>soil quality</u> (physical, chemical and biological properties) by establishing responsible practices of crop management, handling of agrochemicals and pest control.	INDICATOR 130. Amount in mg of total organic carbon (TOC) measured annually in a hectare of oil palm cultivation	(FAO 2012) (Musango et al. 2012) (Edgard Gnansounou 2011) (McBride et al. 2011) NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. ACCIS, Assured Combinable Crops Scheme GAP, Global Partnership for Good Agricultural Practice IFOAM, International Federation of Organic Agriculture Movements LEAF, Linking Environment and Farming GBEP, Global Bioenergy Partnership ISCC, International Sustainability and Carbon Certification SAN/RA, Sustainable Agriculture Network/Rain forest Alliance
	INDICATOR 131. Amount in mg of total nitrogen measured annually in a hectare of oil palm cultivation	
	INDICATOR 132. Amount in mg of extractable phosphorus measured annually in a hectare of oil palm cultivation	
	INDICATOR 133. Annual measure of bulk density in soils in g/cm ³ used for growing oil palm	
	INDICATOR 134. Amount in tons of agrochemical (fertilizers minerals or organics and pesticides) used per hectare of cultivation of palm oil. In special, the agrochemicals prohibited in the Stockholm and Rotterdam Conventions	
	INDICATOR 135. Quantity annual of land, in region with influence of oil palm cultivation for biodiesel, those are degraded due to acidification and the salinization.	
	INDICATOR 136. Quantity (hectares per year) of eroded land in the direct influence of the production of biodiesel	
	INDICATOR 137. Existence of crop rotation plan / cycle. This plan will identify annual cropping for current year and the intentions for the future (over three years).	
PRINCIPLE 11. Biodiesel supply chain must have a positive balance of greenhouse gas, and maintain or promote carbon sinks		
CRITERION 35: The amount of <u>greenhouse gas</u> captured or stored in carbon sinks (biomass associated) must be greater than the amount of greenhouse gas emitted by the biodiesel supply chain.	INDICATOR 138. Tons equivalent CO ₂ emitted by direct change of use of one hectare of land, multiplied by the total annual number of hectares that suffered a direct change in the land use in the area of direct influence of the biodiesel production system.	(BID et MMEC 2012) (FAO 2012) (Musango et al. 2011) (Musango et al. 2012) (Edgard Gnansounou 2011) (E Gnansounou et al. 2009) (Wang, Calderon, et Lu 2011)
	INDICATOR 139. Generated tons of nitrogen oxide associated with the use of chemical fertilizers and pest control on a hectare of palm oil for biodiesel production.	
		BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation BioNa Dv, Biomass Sustainability order, Germany GQA, Genesis Quality Assurance RTRS, Roundtable for Responsible Soy Production GGLS2, Green Gold Label 2. Agriculture Source Criteria Nordic Ecolabelling of Fuels RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RFS2, Renewable Fuel Standard, the United States, 2010 RTFO, Renewable Transport Fuel Obligation – UK Directive 2009/28/EC of the European Union BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation Bonsucro, Better Sugarcane Initiative Interamerican Development Bank-Sustainability Scorecard Bonsucro, Better Sugarcane Initiative GQA, Genesis Quality Assurance RTRS, Roundtable for Responsible Soy Production GGLS2, Green Gold Label 2. Agriculture Source Criteria RSB, Roundtable on Sustainable Biofuels RSPO, Roundtable on Sustainable Palm Oil SBA, Sustainable Biodiesel Alliance RTFO, Renewable Transport Fuel Obligation – UK Social Fuel seal – Brazil Directive 2009/28/EC of the European Union BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation BioNa Dv, Biomass Sustainability order, Germany GBEP, Global Bioenergy Partnership ISCC, International Sustainability and Carbon Certification GGLS2, Green Gold Label 2. Agriculture Source Criteria UNCTAD Biofuels Initiative UNEP, 2009. Towards Sustainable Production

ENVIRONMENTAL DIMENSION OF SUSTAINABILITY		References
	INDICATOR 140. Tons annual equivalent CO2 emitted by the extraction of oil and transformation plants of biodiesel in the production of one tons of biodiesel	(Oviedo et al. 2011) (Kim, Kim, et Dale 2009) (Timilsina et Shrestha 2011) (Szarka, Kakucs, et Bezama 2008) (Wang, Calderon, et Lu 2011) (McBride et al. 2011) (Gudmundsson 2012) (Buchholz, Luzadis, et Volk 2009) (Kurka et Blackwood 2013) NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. Sustainability Guide in Biomass Production and Processing in the Biofuel chain in Colombia ISO 14040 – Life Cycle Assessment Bonsucro, Better Sugarcane Initiative RTRS, Roundtable for Responsible Soy Production RFS2 United States (Epa 2010)
	INDICATOR 141. Annual tons of CO2 equivalent emitted by vehicle engines to use biodiesel in relation to the total annual tons of biodiesel consumed in the transport sector	
	INDICATOR 142. Tons equivalent CO2 emitted annually by indirect change of use of one hectare of land, multiplied by the total annual number of hectares that suffered an indirect change in the land use in the area of direct influence of the biodiesel production system	
	INDICATOR 143. Tons equivalent CO2 emitted by activities of logistic chain relationship with of biodiesel production system per tons of biodiesel produced.	
	INDICATOR 144. Tons of CO2 equivalent annually captured or maintained in carbon sinks	
PRINCIPLE 12. Biodiesel supply chain must promote the conservation and protection of biodiversity and wildlife.		
CRITERION 36: Transformation of natural ecosystems and loss of native natural landscape should be avoided during biomass cultivation and biodiesel production.	INDICATOR 145. Land used (ha/year) for foods crops different to palm oil cultivation for biodiesel.	(FAO 2012) (Edgard Gnansounou 2011) (Groom, Gray, et Townsend 2008) (Timilsina et Shrestha 2011) (McBride et al. 2011) (Buchholz, Luzadis, et Volk 2009) (Markevičius et al. 2010) FSC, Forest Stewardship Council NTA 8080, Sustainable Production of Biomass—The Netherlands CSBP, Council on Sustainable Biomass Production, the United States. ACCS, Assured Combinable Crops Scheme LEAF, Linking Environment and Farming Sustainability Guide in Biomass Production and Processing in the Biofuel chain in Colombia ISO 14040 –Life Cycle Assessment Interamerican Development Bank-Sustainability Scorecard Bonsucro, Better Sugarcane Initiative GQA, Genesis Quality Assurance
	INDICATOR 146. Amount annual of hectare land used for palm oil crop to be transformed in biodiesel	
	INDICATOR 147. Conxant index Equivalent Area (ACE) for evaluating the connectivity ecosystem	
	INDICATOR 148. Annual amount of biodiversity projects and promotion of local traditional knowledge, with the participation of communities	
	INDICATOR 149. Annual amount of degraded land (e.g. erosion, salinization, acidification, or other causes) and areas of natural cover change, in areas directly affected by oil palm plantations or processors biodiesel.	
CRITERION 37: Biodiesel supply chain must preserve areas with fragile ecosystems (both terrestrial and aquatic ecosystems) such as nature reserves defined by the national environmental legislation.	INDICATOR 150. Amount of land (ha) used for forests and natural ecosystems in direct area of influence of palm oil plantation and biodiesel transformation plant, per year	PEFC, Program for the Endorsement of Forest Certification schemes RTRS, Roundtable for Responsible Soy Production GGLS2, Green Gold Label 2. Agriculture Source Criteria Nordic Ecolabelling of Fuels RSB, Roundtable on Sustainable Biofuels RFS2, Renewable Fuel Standard, the United States, 2010 RTFO, Renewable Transport Fuel Obligation –UK Directive 2009/28/EC of the European Union BLCAO, Biofuels life cycle assessment ordinance Swiss Confederation BioNa Dv, Biomass Sustainability order, Germany SAN/RA, Sustainable Agriculture Network/Rain forest Alliance
	INDICATOR 151. Average annual temperature of aquatic ecosystems (e.g. estuaries, rivers, lakes, wetlands) located in the area of direct influence of the oil palm plantations and transformation of biodiesel.	
	INDICATOR 152. Aquatic oxygen demand of aquatic ecosystems (e.g. estuaries, rivers, lakes, wetlands) located in the area of direct influence of the oil palm plantations and transformation of biodiesel.	
CRITERION 38: The number of species of wildlife listed as vulnerable or endangered should not be affected during biomass cultivation and processing of biodiesel.	INDICATOR 153. Number annual of species of fauna and flora, specifically those who are in danger or are considered of special conservation interest, for The International Union for Conservation of Nature (IUCN) and local research organizations.	
	INDICATOR 154. Areas established as wildlife reserves (e.g. national parks, reserves civil society or private reserve areas) located in the area of direct influence of the oil palm plantations and plants	
PRINCIPLE 13. Energy efficiency and use of renewable energy should be promoted in the processes that are part of the biodiesel supply chain		
CRITERION 39: Energy used in the biodiesel supply chain from renewable sources.	INDICATOR 155. Report total annual fuel consumption from renewable fuel sources in joules or multiples, including fuel types used	(Musango et al. 2011) (Edgard Gnansounou 2011) (Wang, Calderon, et Lu 2011) (McBride et al. 2011) (Buchholz, Luzadis, et Volk 2009) (Markevičius et al. 2010) (Kurka et Blackwood 2013) LEAF, Linking Environment and Farming ISO 14040 – Life Cycle Assessment SBA, Sustainable Biodiesel Alliance
	INDICATOR 156. Report total annual fuel consumption from non-renewable sources in joules or multiples, including fuel types used	
CRITERION 40: Energy savings in the biodiesel supply chain with compared to the previous year.	INDICATOR 157. Amount of energy generated for a kg of biodiesel / Amount of energy consumed in the extraction stages and palm oil to biodiesel oil transformation per kilogram of biodiesel [$\sum(\text{kJ Electricity} + \text{kJ Fuel Oil} + \text{kJ Gas} + \text{kJ Coal} + \text{kJ Steam} + \text{kJ Other})/\text{kg biodiesel}$]	

Appendix 2. Constant of equations model

<i>Equation</i>	<i>A1</i>	<i>A2</i>	<i>A3</i>	<i>A4</i>	<i>A5</i>	<i>A6</i>
<i>Equation 3-1</i>	10099512	344.4				
<i>Equation 3-2</i>	3.7E-02	9.7E-3				
<i>Equation 3-3</i>	1.04					
<i>Equation 3-4</i>	3.85					
<i>Equation 3-5</i>	--	--	--	--	--	--
<i>Equation 3-6</i>	417	1.14				
<i>Equation 3-7</i>	--	--	--	--	--	--
<i>Equation 3-8</i>	0.2	1.36				
<i>Equation 3-9</i>	395	1.6E-2				
<i>Equation 3-10</i>	--	--	--	--	--	--
<i>Equation 3-11</i>	--	--	--	--	--	--
<i>Equation 3-12</i>	217	0.6	7.5E-04			--
<i>Equation 3-13</i>	2.12					
<i>Equation 3-14</i>	605281	122712				
<i>Equation 3-15</i>	--	--	--	--	--	--
<i>Equation 3-16</i>	0.11					
<i>Equation 3-17</i>	--	--	--	--	--	--
<i>Equation 3-18</i>	--	--	--	--	--	--
<i>Equation 3-19</i>	--	--	--	--	--	--
<i>Equation 3-20</i>	--	--	--	--	--	--
<i>Equation 3-21</i>	43.1	1.1	43.2	8.7	0.9	--
<i>Equation 3-22</i>	992.9	7.6	992.9	10.3	1.5	
<i>Equation 3-23</i>	--	--	--	--	--	--
<i>Equation 3-24</i>	--	--	--	--	--	--
<i>Equation 3-25</i>	--	--	--	--	--	--
<i>Equation 3-26</i>	-282.6	1.5	141.0	2	1.5	16.7
<i>Equation 3-27</i>	95081	483				
<i>Equation 3-28</i>	0.9					
<i>Equation 3-29</i>	--	--	--	--	--	--
<i>Equation 3-30</i>	--	--	--	--	--	--
<i>Equation 3-31</i>	3.7	6.5E-07	1.3E-06			
<i>Equation 3-32</i>	2.2	0.1				
<i>Equation 3-33</i>	--	--	--	--	--	--
<i>Equation 3-34</i>	--	--	--	--	--	--
<i>Equation 3-35</i>	370.4	29119.2	2197.5	5057.5		
<i>Equation 3-36</i>	--	--	--	--	--	--
<i>Equation 3-37</i>	--	--	--	--	--	--
<i>Equation 3-38</i>	1.1	0.1	3.3			
<i>Equation 3-39</i>	--	--	--	--	--	--
<i>Equation 3-40</i>	25158227	0.4	0.5	11.4		
<i>Equation 3-41</i>	--	--	--	--	--	--
<i>Equation 3-42</i>	4909710	0.3	1.3E-02	0.3		
<i>Equation 3-43</i>	4106272.2	67124.7				
<i>Equation 3-44</i>	--	--	--	--	--	--
<i>Equation 3-45</i>	--	--	--	--	--	--

<i>Equation</i>	<i>A1</i>	<i>A2</i>	<i>A3</i>	<i>A4</i>	<i>A5</i>	<i>A6</i>
<i>Equation 3-46</i>	--	--	--	--	--	--
<i>Equation 3-47</i>	--	--	--	--	--	--
<i>Equation 3-48</i>	--	--	--	--	--	--
<i>Equation 3-49</i>	--	--	--	--	--	--
<i>Equation 3-50</i>	--	--	--	--	--	--
<i>Equation 3-51</i>	2.4	29.9	91.8	135.1		
<i>Equation 3-52</i>	--	--	--	--	--	--
<i>Equation 3-53</i>	--	--	--	--	--	--
<i>Equation 3-54</i>	183582	0.3				
<i>Equation 3-55</i>	2987016	2.2				
<i>Equation 3-56</i>	0.9	4.4E-09	7.1E-08	1.9E-05	3.5E-09	2.7E-08
<i>Equation 3-57</i>	--	--	--	--	--	--
<i>Equation 3-58</i>	--	--	--	--	--	--
<i>Equation 3-59</i>	--	--	--	--	--	--
<i>Equation 3-60</i>	--	--	--	--	--	--
<i>Equation 3-61</i>	--	--	--	--	--	--
<i>Equation 3-62</i>	--	--	--	--	--	--
<i>Equation 3-63</i>	--	--	--	--	--	--
<i>Equation 3-64</i>	--	--	--	--	--	--
<i>Equation 3-65</i>	--	--	--	--	--	--
<i>Equation 3-66</i>	--	--	--	--	--	--
<i>Equation 3-67</i>	--	--	--	--	--	--
<i>Equation 3-68</i>	--	--	--	--	--	--
<i>Equation 3-69</i>	--	--	--	--	--	--
<i>Equation 3-70</i>	--	--	--	--	--	--
<i>Equation 3-71</i>	--	--	--	--	--	--
<i>Equation 3-72</i>	--	--	--	--	--	--
<i>Equation 3-73</i>	--	--	--	--	--	--
<i>Equation 3-74</i>	--	--	--	--	--	--
<i>Equation 3-75</i>	--	--	--	--	--	--
<i>Equation 3-76</i>	--	--	--	--	--	--
<i>Equation 3-77</i>	--	--	--	--	--	--
<i>Equation 3-78</i>	--	--	--	--	--	--
<i>Equation 3-79</i>	--	--	--	--	--	--
<i>Equation 3-80</i>	--	--	--	--	--	--
<i>Equation 3-81</i>	--	--	--	--	--	--
<i>Equation 3-82</i>	--	--	--	--	--	--
<i>Equation 3-83</i>	--	--	--	--	--	--
<i>Equation 3-84</i>	--	--	--	--	--	--
<i>Equation 3-85</i>	--	--	--	--	--	--
<i>Equation 3-86</i>	--	--	--	--	--	--
<i>Equation 3-87</i>	--	--	--	--	--	--
<i>Equation 3-88</i>	--	--	--	--	--	--
<i>Equation 3-89</i>	--	--	--	--	--	--
<i>Equation 3-90</i>	0.002168	0.7111	0.2484			
<i>Equation 3-91</i>	--	--	--	--	--	--
<i>Equation 3-92</i>	0.002168	0.7111	0.2484			

<i>Equation</i>	<i>A1</i>	<i>A2</i>	<i>A3</i>	<i>A4</i>	<i>A5</i>	<i>A6</i>
<i>Equation 3-93</i>	--	--	--	--	--	--
<i>Equation 3-94</i>	0.004	1.03	0.37			
<i>Equation 3-95</i>	--	--	--	--	--	--
<i>Equation 3-96</i>	0.1					
<i>Equation 3-97</i>	--	--	--	--	--	--
<i>Equation 3-98</i>	--	--	--	--	--	--
<i>Equation 3-99</i>	--	--	--	--	--	--
<i>Equation 3-100</i>	--	--	--	--	--	--
<i>Equation 3-101</i>	--	--	--	--	--	--
<i>Equation 3-102</i>	--	--	--	--	--	--

Appendix 3. Model indicator: statistics issues

SD model is defined based on current conditions of biodiesel production in Colombia. This appendix each endogenous indicator established in SD model is defined an equation and its statistical validation. The equations are defined through simulation of different variables and functions. The functions are proposed depend of time trend observed in historical data.

The selection process of the equations is as follows:

- 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:

$$"F - test \text{ Analysis of Variance } "> "F \text{ table } (\alpha; \sqrt{1}, \sqrt{2})"$$

$$\alpha = 0,10$$

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. That is depend of amount of data.
- 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.

For that, it is used statistic software Minitab®. Historical annual data from 1999 to 2013 are used in equation definition. In Table A2-1.

Table A2-1. Analysis of variance.

Variation source	Degrees of freedom	Sum-of-squares	Average squares	F
Due to the regression	k	SSR	$MSR = SSR/n$	$\frac{MRS}{MSE}$
Due to error	$n - k - 1$	SSE	$MSE = SSE/n - k - 1$	
Total	$n - 1$	SST		

Due:

$$SSE = \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

$$SSR = \sum_{i=1}^n (\hat{y}_i - \bar{y})^2$$

$$SST = \sum_{i=1}^n (y_i - \bar{y})^2$$

k = Number of explanatory variables

n = Sample size

The following hypothesis can be tested using the analysis of variance table values:

$$H_0: B_1 = B_2 = \dots = 0$$

$$H_1: B_1 \neq B_2 \neq \dots \neq 0$$

In where H_0 is rejected if the statistical F given by the table of analysis is more to the F_{table} for $\alpha \leq 0,10$.

This condition requires that the selected relationships have a 90% confidence.

$$F = \frac{\frac{SSR}{k}}{\frac{SSE}{n-k-1}}$$

The coefficient of determination R^2 shows the percentage of variability of the response variable, which is explained by the relationship with the independent variables.

$$R^2 = \frac{SSR}{SST}$$

This value increases to add explanatory variables, so it is advisable to use the statistical $R^2_{adjusted}$

$$R^2 = \frac{MSR}{MST} = 1 - (1 - R^2) * \frac{n - 1}{n - k - 1}$$

Then with the data generated by the SD model, is the calculation of the accuracy of the forecast with the data of the year 2011-2013 through the following indicator:

Absolute percentage error of the average (MAPE):

$$MAPE = \frac{\sum_{t=1}^N \left| \frac{Real\ Data - Predicted\ Data_t}{Real\ Data_t} \right|}{N}$$

Table A2-2 Endogenous indicators

#	Endogenous indicators	Symbol
1	Biodiesel production of first generation in Colombia	BdPr1G

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MxRtBdDi	0	0	0	0	0	0	0	0	0	0.05	0.06	0.07	0.08	0.09	0.098
Biodiesel production costs - BPC_1G	0	0	0	0	0	0	0	0	0	1185	1004	1225	1409	1205	1299
BdPr1G	0	0	0	0	0	0	0	0	0	22730	169411	337713	443037	489991	503337

Data utilized: 2008-2013

Regression Analysis: BdPr1G versus Mix_Ratio_Biodie, BPC_1G
 The regression equation is
 BdPr1G = 10101797 Mix_Ratio_Biodiesel_and_Diesel - 345 BPC_1G

Predictor	Coef	SE Coef	T	P
Noconstant				
Mix_Ratio_Biodiesel_and_Diesel	10101797	2625953	3.85	0.018
BPC_1G	-344.6	163.7	-2.11	0.103

S = 90177.6

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	8.00460E+11	4.00230E+11	49.22	0.002
Residual Error	4	32527990657	8131997664		
Total	6	8.32988E+11			

Final equation : Finally, we must to restrict the production in base to production capacity:
 if time>8 then (if 10099512*Mix_Ratio_Biodiesel_and_Diesel-344.4*BPC_1G<BdPrCap then 10099512*Mix_Ratio_Biodiesel_and_Diesel-344.4*BPC_1G else BdPrCap) else 0

2	Biodiesel Sale first generation in Colombia	BdSale																																																																
	<table border="1"> <thead> <tr> <th>Year</th> <th>1999</th> <th>2000</th> <th>2001</th> <th>2002</th> <th>2003</th> <th>2004</th> <th>2005</th> <th>2006</th> <th>2007</th> <th>2008</th> <th>2009</th> <th>2010</th> <th>2011</th> <th>2012</th> <th>2013</th> </tr> </thead> <tbody> <tr> <td>t</td> <td>0</td> <td>1</td> <td>2</td> <td>3</td> <td>4</td> <td>5</td> <td>6</td> <td>7</td> <td>8</td> <td>9</td> <td>10</td> <td>11</td> <td>12</td> <td>13</td> <td>14</td> </tr> <tr> <td>BdPr1G</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>22730</td> <td>169411</td> <td>337713</td> <td>443037</td> <td>489991</td> <td>503337</td> </tr> <tr> <td>BdSale</td> <td>0</td> <td>169065</td> <td>337718</td> <td>518794</td> <td>488187</td> <td>505710</td> </tr> </tbody> </table>	Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	BdPr1G	0	0	0	0	0	0	0	0	0	22730	169411	337713	443037	489991	503337	BdSale	0	0	0	0	0	0	0	0	0	0	169065	337718	518794	488187	505710	
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013																																																			
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14																																																			
BdPr1G	0	0	0	0	0	0	0	0	0	22730	169411	337713	443037	489991	503337																																																			
BdSale	0	0	0	0	0	0	0	0	0	0	169065	337718	518794	488187	505710																																																			

Data utilized: 2008-2013

Regression Analysis: BdSale versus BdPr1G
 The regression equation is
 BdSale = 1.04 BdPr1G 1

Predictor	Coef	SE Coef	T	P
Noconstant				
BdPr1G_1	1.03998	0.03442	30.22	0.000

S = 31412.0

Analysis of Variance						
Source	DF	SS	MS	F	P	
Regression	1	9.00919E+11	9.00919E+11	913.05	0.000	
Residual Error	5	4933557562	986711512			
Total	6	9.05853E+11				

Final equation : 1.03997663*BdPr1G

3	Biodiesel production capacity first generation														BdPrCap
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BdPrCap	0	0	0	0	0	0	0	0	0	180000	520000	520000	520000	520000	520000
CostBdPol										59512.4	80044.5	115409.9	135275.4	144596.8	162312.

Data utilized: 2008-2013

Regression Analysis: BdPrCap versus Cost_linked_to_Biodisel_Politic

The regression equation is
 BdPrCap = 3.85 CostBdPol

Predictor	Coef	SE Coef	T	P
Noconstant				
Cost_linked_to_Biodisel_Politic	3.8536	0.3836	10.05	0.000

S = 114334

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.31904E+12	1.31904E+12	100.90	0.000
Residual Error	5	65361246837	13072249367		
Total	6	1.38440E+12			

Final equation : if time>8 then (3.85* CostBdPol) else 0

4	Profit biodiesel production first generation														ProfitBdPr
ProfitBdPr = BdPrice - BdPrCosts															

5	Biodiesel price														BdPrice
---	-----------------	--	--	--	--	--	--	--	--	--	--	--	--	--	---------

The price of biodiesel was obtained from the report submitted by the UPME. The original price was reported in pesos per gallon, changing units was made biodiesel with a density of 0.88 kg / l, and converted to dollars using an annual average exchange rate given by the Bank of the Republic of Colombia.

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BdPrice	0	0	0	0	0	0	0	0	0	1209.38	1072.67	1267.4	1513.81	1422.86	1319.37
PalmOil Price	377	261	238	357	410	435	368	417	719	634	644	809	966	845	764

Data utilized: 2008-2013

Regression Analysis: BdPrice versus PalmOilPrice

The regression equation is
 BdPrice = 417 + 1.14 PalmOilPrice

Predictor	Coef	SE Coef	T	P
Constant	416.8	191.6	2.17	0.095
PalmOilPrice	1.1379	0.2440	4.66	0.010

S = 68.8619 R-Sq = 84.5% R-Sq(adj) = 80.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	103165	103165	21.76	0.010
Residual Error	4	18968	4742		
Total	5	122133			

Final equation : if time>8 then 417+1.14*PalmOilPrice else 0

6	Diesel price (price of diesel and biodiesel blended)														Dprice
---	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--------

The annual average prices were used in Colombia, including tax surcharge. Original source values were reported in pesos per gallon, changing units was performed with a density of diesel 0,845kg / l, and the price of Colombian pesos was transformed into US dollars using an annual average exchange rate given by Banco de la Republica de Colombia

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
DPrice	339	312	306	306	331	423	551	647	829	984	909	1143	1321	1313	1416
BdPrice	0	0	0	0	0	0	0	0	0	1209.38	1072.67	1267.4	1513.81	1422.86	1319.37
Oil_Price	147.4	231.5	198	199.5	236.9	316.4	431.7	503.4	551.3	759.6	472.2	605.8	723.1	716.8	746.4

Data utilized: 1999-2013

Regression Analysis: DPrice versus BdPrice, Oil_Price

The regression equation is
 $DPrice_1 = 0.208 \text{ BdPrice}_1 + 1.36 \text{ Oil_Price}$

Predictor	Coef	SE Coef	T	P
Noconstant				
BdPrice_1	0.20843	0.06154	3.39	0.005
Oil_PriCe	1.3620	0.1010	13.48	0.000

S = 105.429

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	10528033	5264016	473.59	0.000
Residual Error	13	144497	11115		
Total	15	10672530			

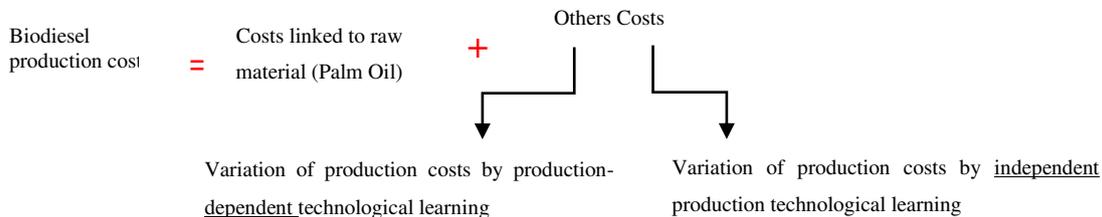
Final equation : $0.208 * \text{BdPrice} + 1.36 * \text{Oil_Price}$

Units

$$\frac{\text{Pesos}}{\text{Galon}} \times \frac{1 \text{ Galon}}{3,78 \text{ litros}} \times \frac{1 \text{ litro}}{0,845 \text{ kg}} \times \frac{1000 \text{ kg}}{1 \text{ Ton}} \times \frac{1 \text{ USD}}{\text{Tasa de cambio Pesos}}$$

7 Biodiesel production costs first generation BdPrCosts

The cost of biodiesel production, from the point of view of technological learning, may arise in the following way:



The following describes how was calculated each of the variables that make up the equation:

- Cost of biodiesel production: are calculated annually as a variable cost depending on the price of palm oil and other costs on the basis of the selling price of biodiesel. To calculate the costs associated with the raw material, which in the case of Colombia is the palm oil, was established the stoichiometric ratio between the amount of palm oil needed to produce a ton of biodiesel, this relationship was 1.02 tPalmOil/t Biodiesel. Then the cost of palm oil to produce a ton of biodiesel will be the multiplication of 1.02 tPalmOil/t Biodiesel for the price of palm oil in the corresponding year. The second stage was to establish other production costs and their relationship the price of biodiesel. According to Ong (2012) and Acevedo (2015) other costs are between 170,6-310,6 USD/t Biodiesel, and finding the value average value that relate with the selling price of biodiesel in Colombia between 2008 and 2013, would be 20% of the selling price of biodiesel.

Technological learning could only influence the other costs of production of biodiesel. Learning analysis production-dependent and independent of this as well:

Variation of production costs by production-dependent technological learning:

To determine the dependent production technological learning curves, is required to know the accumulated production of biodiesel, the initial costs of production and the rate of learning. With this information the following equations can be applied:

$$\text{Equation 1. } Costo_{Fut} = Costo_{Ini} * (\text{Producción}_{Acum})^b$$

$$PR = 2^b$$

Where:

Cost_{Fut}= Cost of production at the moment t

Cost_{Ini}= Initial production cost

Production_{Acum}= Accumulated production of biodiesel for the moment t

PR = Learning rate
b= Constant factor

According to Espinoza (2015) assumed b = - 0,0163.

If this value is replaced in the equation (2) is obtained that:PR= 2^{-0.0163}= 98,875%. This means that there is a reduction in costs of 1,125% every time you bend the accumulated production of biodiesel.

The calculation of the cumulative production-dependent learning curve can be with this estimate of b. Applying equation (1) to consider that:

$$Cost_{ini}(90\%) = 1185 \frac{USD}{t} Biod$$

The initial costs are costs defined in the first year of operation, which was in 2008.

It is important to remember that the total cost of producing biodiesel is divided into two parts, the first are the costs associated with Palm oil biodiesel production, and the second are other cost. It is on the other costs that can occur with a technological learning. Therefore the estimated cost of production-dependent technological learning is calculated using Equation 1.

OTHER independent of the cumulative production of biodiesel estimated costs are calculated:

$$BdPrCost_{Others} = BdPrCosts_{Others} - BdPrCosts_{Other Production Depend}$$

It is gets the following table of costs estimated:

t	BdPr1G	Acumulated biodiesel production	BdPrCosts	BdPrCost linked_to_OilPalm_Price	BdPrCosts-Others	Others_BdPr_Cost Dependent_of_BdPr	Others BdPr_Cost Independent_of_BdPr
9	22730	22730	1185	800	385	385	0
10	169411	192141	1004	790	215	315,53	-101
11	337713	529854	1225	997	228	310,36	-82
12	443037	972891	1409	1137	272	307,30	-35
13	489991	1462882	1205	911	293	305,26	-12
14	503337	1966219	1335	1035	299	303,80	-4,3

The calculation of other independent of the cumulative production of biodiesel estimated costs, are those costs than other types of learning technology, external to the production of biodiesel, contributed to the reduction of costs. To explain this decrease in costs not associated with the production, discussed the relationship with the generation of patents and scientific papers globally on the production of first generation biodiesel

if time>8 then

(Others_BdPr_Cost_Independent_of_BdPr+Others_BdPr_Cost_Dependent_of_BdPr+BdPr_Cost_linked_to_OilPalm_Price) else 0

8	Others biodiesel production costs depend of biodiesel production	OthBdPrCostsDepPr
if time >8 then 385*Accumulated_Production_of_biodiesel_1G^-0.0163 else 0		

9	Biodiesel production costs linked to Palm oil Price	BdPrCostsPalmOilPrice
if time>8 then EffFactTecPalmOilBd *PalmOilPrice else 0		

10	Palm oil price	PalmOilPrice																																																																																
	<table border="1"> <thead> <tr> <th>Year</th> <th>1999</th> <th>2000</th> <th>2001</th> <th>2002</th> <th>2003</th> <th>2004</th> <th>2005</th> <th>2006</th> <th>2007</th> <th>2008</th> <th>2009</th> <th>2010</th> <th>2011</th> <th>2012</th> <th>2013</th> </tr> </thead> <tbody> <tr> <td>t</td> <td>0</td> <td>1</td> <td>2</td> <td>3</td> <td>4</td> <td>5</td> <td>6</td> <td>7</td> <td>8</td> <td>9</td> <td>10</td> <td>11</td> <td>12</td> <td>13</td> <td>14</td> </tr> <tr> <td>PalmOilPrice</td> <td>377</td> <td>261</td> <td>238</td> <td>357</td> <td>410</td> <td>435</td> <td>368</td> <td>417</td> <td>719</td> <td>634</td> <td>644</td> <td>809</td> <td>966</td> <td>845</td> <td>764</td> </tr> <tr> <td>PalmOilStoBd</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>0</td> <td>24094</td> <td>179576</td> <td>357976</td> <td>469619</td> <td>519390</td> <td>533537</td> </tr> <tr> <td>Oil_Price</td> <td>147</td> <td>231</td> <td>198</td> <td>199</td> <td>237</td> <td>316</td> <td>432</td> <td>503</td> <td>551</td> <td>760</td> <td>472</td> <td>606</td> <td>723</td> <td>717</td> <td>746</td> </tr> </tbody> </table>	Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	PalmOilPrice	377	261	238	357	410	435	368	417	719	634	644	809	966	845	764	PalmOilStoBd	0	0	0	0	0	0	0	0	0	24094	179576	357976	469619	519390	533537	Oil_Price	147	231	198	199	237	316	432	503	551	760	472	606	723	717	746	
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013																																																																			
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Oil_Price	147	231	198	199	237	316	432	503	551	760	472	606	723	717	746																																																																			

Data utilized: 1999-2009

Regression Analysis: PalmOilPrice_1 versus PalmOilStoBd_1, Oil_Price_2

The regression equation is

$$PalmOilPrice_1 = 217 + 0.000858 PalmOilStoBd_1 + 0.569 Oil_Price_2$$

Predictor	Coef	SE Coef	T	P
Constant	216.66	68.52	3.16	0.013
PalmOilStoBd_1	0.0008579	0.0006122	1.40	0.199
Oil_Price_2	0.5687	0.1728	3.29	0.011

S = 100.384 R-Sq = 67.4% R-Sq(adj) = 59.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	166783	83391	8.28	0.011
Residual Error	8	80615	10077		
Total	10	247398			

Final equation : 217+0.572*Oil_Price+0.000747*PalmOilStoBd

11	Diesel consumed in transport sector	DiConsTransp																																
	<table border="1"> <thead> <tr> <th>Year</th> <th>1999</th> <th>2000</th> <th>2001</th> <th>2002</th> <th>2003</th> <th>2004</th> <th>2005</th> <th>2006</th> <th>2007</th> <th>2008</th> <th>2009</th> <th>2010</th> <th>2011</th> <th>2012</th> <th>2013</th> </tr> </thead> <tbody> <tr> <td></td> </tr> </tbody> </table>	Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013																	
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013																			

t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
DiConsTransp	1434533.3	1763066.7	2525600	1766800	1983333.3	2579733.3	2863466.7	3309600	3332933.3	3513066.7	3770666.7	3767866.7	4714266.7	5010133.3	4659722.7
DieselVehicles	605282	727994	850706	973418	1096130	1218842	1341554	1458486	1580586	1744307	1843738	1912869	2056526	2230321	2323254.48

Data utilized: 1999-2013

Regression Analysis: DiConsTransp versus Diesel_Vehicles

The regression equation is
 $DiConsTransp = 2.12 Diesel_Vehicles$

Predictor	Coef	SE Coef	T	P
Noconstant				
Diesel_Vehicles	2.12350	0.04965	42.77	0.000

S = 299488

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.64056E+14	1.64056E+14	1829.08	0.000
Residual Error	14	1.25570E+12	89693035111		
Total	15	1.65312E+14			

Final equation : $2.12 * Diesel_Vehicles$

Units :

$$\frac{1 \text{ ktep diesel}}{\text{año}} \times \frac{1000}{1k} \times \frac{42 \text{ GJ}}{1 \text{ tep}} \times \frac{1000 \text{ MJ}}{1 \text{ GJ}} \times \frac{1 \text{ kg diesel}}{45 \text{ MJ}} \times \frac{1 \text{ t diesel}}{1000 \text{ kg diesel}} = \frac{933,33 \text{ t diesel}}{\text{año}}$$

12	Biodiesel consumption estimated in transport sector (DiConsTransp*MxRatBdDi)/(1-MxRatBdDi)	BdConsTransp
----	---	--------------

13	Valorization of glycerol by PDO GlyPr* TFPOD *0.4*0.677	PDOGly
----	--	--------

14	Glycerol production 0.11*BdPr1G	GlyPr
----	------------------------------------	-------

15	Factor valorization PDO IF MxRtBdDi>0.12 THEN (MxRtBdDi+MxRtBdD*0.1) ELSE 0	FactorValorizPDO
----	--	------------------

16	Total biodiesel production BdPr1G+ Bd2&3G	TotalBdPr
----	--	-----------

17	Biodiesel production second and third generation in Colombia if TIME>=20 then BdPr1G*0.10+ FactPromBd2&3G else 0	Bd2&3G
----	---	--------

18	Unsatisfied demand of biodiesel in Colombia - stock BdConsTransp -TotalBdPr	UnsDemandBd
----	--	-------------

19	Promotion factor biodiesel second and third generation in Colombia $FactPromBd2\&3G = \left(\frac{Patent_Bd2\&3G}{Articles_Bd2\&3G} \right) \times IntBdPr2\&3G + \left(\frac{SkUnsDemandBd}{100} \right)$	FactPromBd2&3G
----	---	----------------

20	Index of energy diversity of Colombia The information was based on kilotonnes of oil equivalent (ktoe) secondary energy sources (charcoal, coal, diesel, electricity, fuel oil, industrial gas, liquefied gas, gasoline engine, refinery gas, kerosene is considered and non-energy) and primary energy sources (hydropower, wood, bagasse, oil, coal, natural gas, industrial waste) in Colombia. From 2009 biodiesel and alcohol fuel is introduced secondary energies. According to The Global Energy Architecture Performance Index Report 2013 Diversity index of Total primary energy supply and secondary (Herfindahi index) it can be used to assess the energy diversity of a country; At higher values it lowers energy diversity. $H = \sum_{i=1}^n s_i^2$	IndexEnDiv
----	--	------------

where "s" breaking the type of energy to the square of the n types of energy that compose

Year	2008	2009	2010	2011	2012	2013
t	9	10	11	12	13	14
IndDivEnergP	0.21	0.21	0.21	0.21	0.22	0.23
TM_1	0	0.05	0.06	0.07	0.08	0.09

Data utilized: 2008-2013

RAPPORT DÉTAILLÉ

Statistiques de la régression

Coefficient de détermination multiple	0.93
Coefficient de détermination R^2	0.87
Coefficient de détermination R^2	0.78
Erreur-type	0.00
Observations	6.00

	Ftable	5.5
ANALYSE DE VARIANCE	Ttable	2.4

	Degré de liberté	Somme des carrés	Moyenne des carrés	F	Valeur critique de F
Régression	2	0.00024	0.00012	9.8	0.04794
Résidus	3	0.00004	0.00001		
Total	5	0.00028			

	Coefficients	Erreur-type	Statistique t	Probabilité	Limite inférieur e pour seuil de confiance e = 95%	Limite supérieur e pour seuil de confiance e = 95%	Limite inférieur e pour seuil de confiance 95,0%	Limite supérieur e pour seuil de confiance = 95,0%
Constant	16.71	6.91	2.42	0.09	-5.27	38.69	-5.27	38.69
cos(TM_1' + 1.45397)	-282.60	118.33	-2.39	0.10	-659.17	93.97	-659.17	93.97
cos(2 * TM_1' + 1.45397)	141.02	59.08	2.39	0.10	-47.01	329.05	-47.01	329.05

Final equation: $-282.567 * \cos(\text{MxRtBdDi} + 1.45397) + 141.001 * \cos(2 * \text{MxRtBdDi} + 1.45397) + 16.707$

21	Palm oil production														PalmOilPr	
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
PalmOilPr	492354	520465	543677	524871	525470	630016	660127	714307	733241	777509	804838	753039	945064	973770	1039785	
CrYieldPalm	4.05	4.09	4.18	3.75	3.58	4.11	4.03	4.02	3.67	3.51	3.41	3	3.54	3.25	3.11	
DPrice	339	312	306	306	331	423	551	647	829	984	909	1143	1321	1313	1416	

Data utilized: 1999-2011

Regression Analysis: PalmOilPr versus Crop_Yield_in_Pa, DPrice

The regression equation is

$\text{PalmOilPr} = 95081 \text{ Crop Yield in Palm Cultivation} + 483 \text{ DPrice}$

Predictor	Coef	SE Coef	T	P
Noconstant				
Crop_Yield_in_Palm_Cultivation	95081	5412	17.57	0.000
DPrice	487.03	35.15	13.86	0.000

S = 32053.2

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	4.48409E+12	2.24205E+12	2182.23	0.000
Residual Error	9	9246695203	1027410578		
Total	11	4.49334E+12			

Source	DF	Seq SS
Crop Yield in Palm Cultivation	1	4.28684E+12
DPrice	1	1.97248E+11

Final equation: $\text{if } (95081 * \text{CrYieldPalm} + 483 * \text{DPrice} < \text{LandP} * \text{CrYieldPalm}) \text{ then } (95081 * \text{CrYieldPalm} + 483 * \text{DPrice}) \text{ else } (\text{LandP} * \text{CrYieldPalm})$

22	Palm oil sales	PalmOilS
----	----------------	----------

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PalmOilPr	492354	520465	543677	524871	525470	630016	660127	714307	733241	777509	804838	753039	945064	973770	1039785
PalmOilS	457555.1	545190.3	552047.3	522608	532673.7	623970.9	669084.3	705530.2	729454.8	774606.1	791841.5	751429.2	941836.6	975857.2	1042863

Data utilized: 1999-2013

Regression Analysis: PalmOilS_1 versus PalmOilPr_1

The regression equation is
 $\text{PalmOils}_1 = 0.998 \text{ PalmOilPr}_1$

Predictor	Coef	SE Coef	T	P
Noconstant				
PalmOilPr_1	0.998020	0.004566	218.56	0.000

S = 12901.9

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	7.95136E+12	7.95136E+12	47767.98	0.000
Residual Error	14	2330410383	166457884		
Total	15	7.95369E+12			

Final equation: $0.998 * \text{PalmOilPr}$

23	Palm oil sales to other uses	PalmOilSoth
PalmOilS-PalmOilStoBd		

24	Palm oil sales to biodiesel	PalmOilStoBd
EffFactTecPalmOilBd*BdPrIG		

25	Crop yield in palm cultivation	CrYieldPalm
----	--------------------------------	-------------

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
CrYieldPalm	4.05	4.09	4.18	3.75	3.58	4.11	4.03	4.02	3.67	3.51	3.41	3	3.54	3.25	3.11
SoilLossPalm	6038045.6	6331459	6839104.3	7494008.1	8629154.7	10078120.8	11333048.9	12373298.8	13346662.4	14897641.7	16307491.1	18080684.5	19226485.9	20357266.6	21490075.7
AgrochemPalm	3294830	3433518	3681612	3997136	4549622	5256394	5940594	6436540	6751338	7413032	7931795.1	8890286	9402096.3	9953570	10489204

Data utilized: 1999-2013

Regression Analysis: CrYieldPalm versus Soil_Loss_in, Agrochemical

The regression equation is
 $\text{CrYieldPalm} = 3.73 - 0.000001 \text{ SoilLossPalm} + 0.000001 \text{ AgrochemPalm}$

Predictor	Coef	SE Coef	T	P
Constant	3.7295	0.4237	8.80	0.000
SoilLossPalm	-0.00000065	0.00000032	-2.02	0.066
AgrochemPalm	0.00000129	0.00000070	1.83	0.092

S = 0.204846 R-Sq = 75.9% R-Sq(adj) = 71.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	1.58239	0.79120	18.86	0.000
Residual Error	12	0.50354	0.04196		
Total	14	2.08593			

Final equation: $3.7302 - 0.00000065 * \text{SoilLossPalm} + 0.0000012803 * \text{AgrochemPalm}$

26	Agrochemicals applied in land for palm cultivation	AgrochemPalm
LandP *FAAPC		

27	Soil loss in palm cultivation	SoilLossPalm
----	-------------------------------	--------------

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

SoilLossPalm	6038045.6	6331459	6839104.3	7494008.1	8629154.7	10078120.8	11333048.9	12373298.8	13346662.4	14897641.7	16307491.1	18080684.5	19226485.9	20357266.6	21490075.7
AgrochemPalm	3294830	3433518	3681612	3997136	4549622	5256394	5940594	6436540	6751338	7413032	7931795.1	8890286	9402096.3	9953570	10489204
ForEcosLand	12949612.5	128926031	2824586.6	12756570.2	12688553.8	12620537.4	12552521	12484504.6	12416488.2	12348471.8	12280455.4	12215785.9	12181588.3	12147486.5	12121982

Data utilized: 1999-2013

Regression Analysis: SoilLossPalm versus Agrochemical, Forests_and_

The regression equation is
 SoilLossPalm = 2.16 AgrochemPalm
 - 0.0922 ForEcosLand

Predictor	Coef	SE Coef	T	P
Noconstant				
AgrochemPalm	2.15672	0.01810	119.13	0.000
ForEcosLand	-0.09221	0.01001	-9.21	0.000

S = 176139

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	2	2.87546E+15	1.43773E+15	46340.92	0.000
Residual Error	13	4.03326E+11	31025071528		
Total	15	2.87586E+15			

Final equation: 2.15672139* AgrochemPalm -0.0922105* ForEcosLand

28	Land for palm cultivation	LandP
LandP (t) = LandP (t - dt) + (VarLandP - DecreaseLandP) * dt		
INIT LandP = 143115		

29	Variation of land for palm cultivation	VarLandP												
VarLandP	6304.0	11277.0	14342.0	25113.0	32126.0	31100.0	22543.0	14309.0	30077.0	23580.1	43567.8	23264.1	25067.0	24347.0
QualEmPalm	-21009.5	-22513.6	-24426.5	-27776.1	-32061.1	-36209.2	-39216.0	-41124.5	-45136.2	-48861.3	-55022.4	-58792.3	-62530.8	-66358.2
CrYieldPalm	4.1	4.2	3.8	3.6	4.1	4.0	4.0	3.7	3.5	3.4	3.0	3.5	3.3	3.1
BdConsTransp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	175417.5	184898.2	240680.9	283602.9	409936.2	495507.7	506267.0
VarPopDispViol	61308	13604	20094	-58189	-639	17697	-14326	2342	-8907	-53420	-16584	-49	340	3021

Data utilized: 1999-2013

Nonlinear Regression: VarLandP = a1 * cos(QualEmPalm) + ...

Method
 Algorithm Gauss-Newton
 Max iterations 200
 Tolerance 0.00001

Starting Values for Parameters
 Parameter Value
 a1 1
 a2 1
 a3 1
 a4 1

Equation:
 VarLandP = -370.376 * cos(QualEmPalm) - 29119.2 * cos(CrYieldPalm) + 2197.48 *
 cos(BdConsTransp) - 5057.52 * cos(VarPopDispViol)

Parameter Estimates

Parameter	Estimate	SE Estimate
a1	-370.4	3881.02
a2	-29119.2	3029.06
a3	2197.5	2648.32
a4	-5057.5	3451.44

VarLandP = a1 * cos(QualEmPalm) + a2 * cos(CrYieldPalm) + a3 *
 cos(BdConsTransp) + a4 * cos(VarPopDispViol)

Summary
 Iterations 2
 Final SSE 804074600
 DFE 10
 MSE 80407460

S	8967.02
Final equation: $\text{VarLandP} = -370.376 \cdot \cos(\text{QualEmPalm}) - 29119.2 \cdot \cos(\text{CrYieldPalm}) + 2197.48 \cdot \cos(\text{BdConsTransp}) - 5057.52 \cdot \cos(\text{VarPopDispViol})$	

30	Decrease of land for palm cultivation	DecreaseLandP
FBd2&3Gha*BdPr2&3G		

31	Agricultural lands	AgrLand
AgrLand (t) = AgrLand (t - dt) + (-VarAgrLand) * dt INIT AgrLand = 2068915		

32	Food security indicator	FoodSecInd
AgrLand/LandP		

33	Variation of agricultural lands	VarAgrLand
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Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
VarAgrLand		-71901.1	44678.9	-427883.2	226292.2	-24688.3	-176641.4	-206819.5	130132.1	-107779.7	-121064.1	-46401.4	-74527.8	-5169.2	-226628.2
LandP	149765	156069	167346	181688	206801	238927	270027	292570	306879	336956	360536.1	404103.9	427368	452435	476782
AgrLand	2096137.5	2024236.4	2068915.4	1641032.1	1867324.3	1842636.1	1665994.6	1459175.2	1589307.2	1481527.5	1360463.4	1314062	1239534.2	1234365	1007736.8
LivLand	23176242.8	23235519	22947711	23283059	23259712	23579130	23861161	23757924	23785137	23985105	23830695	24068360	23268239	23756137.3	24073518.3

Data utilized: 1999-2013

Regression Analysis: VarAgrLand versus Land_for_Pal, Agricultural, ...

The regression equation is

$$\text{VarAgrLand} = 3.28 \text{ LandP} + 1.13 \text{ AgricLand} - 0.120 \text{ LivLand}$$

Predictor	Coef	SE Coef	T	P
Noconstant				
LandP	3.2770	0.8670	3.78	0.003
AgricLand	1.1291	0.2736	4.13	0.002
LivLand	-0.12010	0.02888	-4.16	0.002

S = 108719

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	2.88328E+11	96109258290	8.13	0.004
Residual Error	11	1.30018E+11	11819843638		
Total	14	4.18346E+11			

$$\text{Final equation: } 1.13 \cdot \text{AgricLand} - 0.120 \cdot \text{LivLand} + 3.28 \cdot \text{LandP}$$

34	Livestock land	LivLand
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Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	1	2	3	4	5	6	7	8	9	10	11	12	13	14
LivLand	23235519.0	22947711.0	23283059.0	23259712.0	23579130.0	23861161.0	23757924.0	23785137.0	23985105.0	23830695.0	24068360.0	23268239.0	23756137.3	24073518.3
AgricLand	2024236.4	2068915.4	1641032.1	1867324.3	1842636.1	1665994.6	1459175.2	1589307.2	1481527.5	1360463.4	1314062.0	1239534.2	1234365.0	1007736.8
PooPop	2678981	2699966	2723175	2758452	2359167	2291640	2287760	2273035	1878043	1842059	2311804	2254761	2122471	2004001
VarLandP	6304.0	11277.0	14342.0	25113.0	32126.0	31100.0	22543.0	14309.0	30077.0	23580.1	43567.8	23264.1	25067.0	24347.0

Data utilized: 2000-2013

RAPPORT DÉTAILLÉ

Statistiques de la régression

Coefficient de détermination multiple

Coefficient de détermination R² 0.882

Coefficient de détermination R² 0.842

Erreur-type 206708.39

Observations 13

ANALYSE DE VARIANCE

	Degré de liberté	Somme des carrés	Moyenne des carrés	F	Valeur critique de F
Régression	3	1.2486E+12	4.1621E+11	22.38	0.00258725
Résidus	10	4.2728E+11	4.2728E+10		
Total	13	1.6759E+12			

Ftable 2.72767314

Ttable 1.81246112

Coefficients	Erreur-type	Statistique t	Probabilité	Limite inférieure		Limite supérieure		
				pour seuil de confiance = 95%	pour seuil de confiance = 95%	pour seuil de confiance = 95,0%	pour seuil de confiance = 95,0%	
Constante	25158227	578157.594	62.82	1.0485E-12	23717432.4	26293863.2	23717432.36	26293863.2
AgricLands	-0.4218	0.27729274	-2.04	0.06048401	-0.76780638	0.46788707	-0.767806384	0.46788707
PoorPop	-0.4772	0.28748857	-2.35	0.05312925	-1.27082426	0.01030464	-1.270824264	0.01030464
VarLandP	11.402	6.80548168	2.42	0.07884099	-1.84592058	28.4811957	-1.845920583	28.4811957

Final equation: 25158227 - 0.422 *AgricLand- 0.477 *PoorPop+ 11.4 *VarLandP

35	Forest and ecosystems lands	ForEcosLand
ForEcosLand(t)= ForEcosLand(t-dt)+(-VarForEcosLand)dt INIT ForEcosLand = 13006622 ha		

36	Variation of forest and ecosystems lands	VarForEcosLand
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Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
VarForEcosLand	-57009.5	-57009.5	-68016.4	-68016.4	-68016.4	-68016.4	-68016.4	-68016.4	-68016.4	-68016.4	-68016.4	-64669.5	-34197.6	-34101.8	-25504.5
ForEcosLand	12949612.5	12892603	12824586.6	12756570.2	12688553.8	12620537.4	12552521	12484504.6	12416488.2	12348471.8	12280455.4	12215785.9	12181588.3	12147486.5	12121982
LivLand	23176242.8	23235519	22947711	23283059	23259712	23579130	23861161	23757924	23785137	23985105	23830695	24068360	23268239	23756137.3	24073518.3
PopPalm	4141743	4181458	4237512	4298187	4366354	4434543	4488736	4556952	4639004	4707649	4776817	4846818	4917577	4988642	5060185

Data utilized: 1999-2013

Regression Analysis: VarForEcosLa versus Forests_and_, Livestock_La, ...

The regression equation is

$$\text{VarForEcosLand} = -4909713 + 0.296 \text{ ForEcosLands} - 0.0128 \text{ LivLand} + 0.317 \text{ PopPalm}$$

Predictor	Coef	SE Coef	T	P
Constant	-4909713	705735	-6.96	0.000
ForEcosLands	0.29637	0.03948	7.51	0.000
LivLand	-0.012846	0.005044	-2.55	0.027
PopPalm	0.31676	0.03548	8.93	0.000

S = 4420.18 R-Sq = 93.1% R-Sq(adj) = 91.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	2913828040	971276013	49.71	0.000
Residual Error	11	214917881	19537989		
Total	14	3128745921			

Final equation: - 4909710 + 0.296*ForEcosLand - 0.0128*LivLand + 0.317*PopPalm

37	Biodiversity indicator	BiodivInd
$\text{BiodivInd} = \frac{(FB \times \text{ForEcosland})}{\text{AreaInflPalm}}$		
38	Quality of employment in palm cultivation	QualEmPalm
$\text{QualEmPalm} = \text{BetterQEmPalm} - \text{DetrimQEmPalm}$		
39	Better quality employment in palm cultivation	BetterQEmPalm
$\text{BetterQEmPalm} = \text{DirectEmPalm} + \text{UnionizedEmPalm}$		
40	Total Workers in Palm Cultivation	TotEmPalm
$\text{TotEmPalm} = \text{FTEPC} \times \text{LandP}$		
41	Direct contracts employers in Palm Cultivation	DirectEmPalm
$\text{DirectEmPalm} = \text{FDCE} \times \text{TotEmPalm}$		
42	Unionized employees in Palm Cultivation	UnionizedEmPalm
$\text{UnionizedEmPalm} = \text{FUE} \times \text{TotEmPalm}$		
43	Detriment of quality employment in palm cultivation	DetrimQEmPalm
$\text{DetrimQEmPalm} = \text{Accid\&diseases} + \text{SubcontrEmPalm} + \text{ChildLabPalm}$		
44	Subcontracted employers in Palm Cultivation	SubcontrEmPalm
$\text{SubcontrEmPalm} = \text{FSCE} \times \text{TotEmPalm}$		
45	Child Labour in Palm Cultivation	ChildLabPalm
$\text{ChildLabPalm} = \text{FCLPC} \times \text{TotEmPalm}$		

46	Population displaced by violence	PopDispViol
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Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

PopDispViol	68452	129760	143364	163458	105269	104630	122327	108001	110343	101436	48016	31432	31383	31723	34744
LandP	149765	156069	167346	181688	206801	238927	270027	292570	306879	336956	360536	404103	427368	452435	476782

Data utilized: 1999-2013

Regression Analysis: PopDispViol versus LandP

The regression equation is
 $PopDispViol = 183582 - 0.321 LandP$

Predictor	Coef	SE Coef	T	P
Constant	183582	20636	8.90	0.000
Land for Palm Cultivation	-0.32053	0.06565	-4.88	0.000

S = 27428.6 R-Sq = 64.7% R-Sq(adj) = 62.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	17931458264	17931458264	23.83	0.000
Residual Error	13	9780280454	752329266		
Total	14	27711738718			

Final equation: $183582 - 0.321 * LandP$

47	Poor population	PoorPop
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Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PoorPop	2652657	2678981	2699966	2723175	2758452	2359167	2291640	2287760	2273035	1878043	1842059	2311804	2254761	2122471	2004001
LandP	149765	156069	167346	181688	206801	238927	270027	292570	306879	336956	360536	404103	427368	452435	476782

Data utilized: 1999-2013

Regression Analysis: PoorPop versus Land_for_Palm_Cultivation_1

The regression equation is
 $PoorPop = 2987016 - 2.18 LandP$

Predictor	Coef	SE Coef	T	P
Constant	2987016	143325	20.84	0.000
LandP	-2.1831	0.4560	-4.79	0.000

S = 190506 R-Sq = 63.8% R-Sq(adj) = 61.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	8.31808E+11	8.31808E+11	22.92	0.000
Residual Error	13	4.71803E+11	36292524857		
Total	14	1.30361E+12			

Final equation: $2987016 - 2.18 * LandP$

48	Land concentration index – GINI	GINI
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Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	2	3	4	5	6	7	8	9	10	11	12	13	14
GINI	0.7659	0.7664	0.7686	0.7711	0.7704	0.7721	0.7750	0.7757	0.7802	0.7707	0.7720	0.7722	0.7711
LivLand	23235519.0	22947711.0	23283059.0	23259712.0	23579130.0	23861161.0	23757924.0	23785137.0	23985105.0	23830695.0	24068360.0	23268239.0	23756137.3
LandP	156069.0	167346.0	181688.0	206801.0	238927.0	270027.0	292570.0	306879.0	336956.0	360536.1	404103.9	427368.0	452435.0
OilPrice	231.5	198.0	199.5	236.9	316.4	431.7	503.4	551.3	759.6	472.2	605.8	723.1	716.8
DiCoSecTransp	1763066.7	2525600	1766800	1983333.3	2579733.3	2863466.7	3309600	3332933.3	3513066.7	3770666.7	3767866.7	4714266.7	5010133.3
BdPr1G	0	0	0	0	0	0	0	0	22730	169411	337713	443037	489991

Data utilized: 2001-2013

Regression Analysis: GINI versus LivLand, LandP, ...

The regression equation is
 $GINI = 0.860 - 0.0000000438 LivLand + 0.000000070782 LandP + 0.00001889 OilPrice - 0.00000000354 DiConsTransp - 0.0000000274 BdPr1G$

Predictor	Coef	SE Coef	T	P
Constant	0.85999	0.04601	18.69	0.000
LivLand	-0.000000000	0.000000000	-2.13	0.070
LandP	0.000000007	0.000000002	3.01	0.020
OilPrice	0.00001889	0.00000433	4.36	0.003
DiConsTransp	-0.000000000	0.000000000	-2.68	0.032
BdPr1G	-0.000000003	0.000000001	-5.08	0.001

S = 0.00100238		R-Sq = 95.9%		R-Sq(adj) = 93.0%	
Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	5	0.000166253	0.000033251	33.09	0.000
Residual Error	7	0.000007033	0.000001005		
Total	12	0.000173287			
Final equation: if (0.85999363-4.386E-9*LivLand+7.0782E-8*LandP+1.8892E-5*OilPrice-3.547E-9*DiConsTransp-2.746E-8*BdPr1G) <1 then 0.85999363-4.386E-9*LivLand+7.0782E-8*LandP+1.8892E-5*OilPrice-3.547E-9*DiConsTransp-2.746E-8*BdPr1G else 1					
49	Biodiesel energy inputs				BdEnInputs
$BdEnInputs = EnPalmCult + EnPalmOilExtr + EnTranstest + EnTransp + EnKernel\&Glycerin$					
50	Energy Palm oil extraction				EnPalmOilExtr
$EnPalmOilExtr = DieselStartup + ElectricityGrid + ElectricityPowerPlant + SteamPowerPlant$					
51	Input Energy Fertilizers				EnFertilizers
$EnFertilizers = Nitrogen_Applied \times Nitrogen_Energy + Phosphate_Applied \times Phosphate_Energy + Potassium_Energy \times Potassium_Applied + Magnesium_Energy + Boron_Energy$					
52	Input Energy Palm Cultivation				EnPalmOilCult
$EnPalmOilCult = EnFertilizers + EnHerbicides + EnIrrWater$					
53	Energy Transesterification				EnTranstest
$EnTranstest = Catalyst_NaOH + Electricity_from_grid2 + Methanol + Steam$					
54	Biodiesel energy output				BdEnOutputs
$BdEnOutputs = EnBd + EnPalmistCake + EnPalmistOil + EnSoaps + EnGlycerol + EnShell$					
55	Biodiesel energy				EnBd
$EnBd = FBdE \times CrYieldPalm$					
56	Palmist cake energy				EnPalmistCake
$EnPalmistCake = FPcE \times CrYieldPalm$					
57	Palmist oil energy				EnPalmistOil
$EnPalmistOil = FPM_e \times CrYieldPalm$					
58	Soaps energy				EnSoaps
$EnSoaps = FSE \times CrYieldPalm$					
59	Glycerol purified energy				EnGlycerol
$EnGlycerol = FGPE \times CrYieldPalm$					
60	Shell energy				EnShell
$EnShell = FShE \times CrYieldPalm$					
61	Net energy ration				NER
$NER = \frac{BdEnOutputs}{BdEnInputs}$					
62	Water demand in geographical regions influenced by biodiesel supply chain				WaterBdSC
$WaterBdSC = WaterP + WaterPalmOilEx + WaterBdPr + WaterPop + WaterLiv + WaterAgr$					
63	Agricultural water demand				WaterAgr
$WaterAgr = AgrLand \times FAWD$					
64	Water demanded in oil palm cultivation				WaterP
$WaterP = LandP \times FWDPC$					
65	Water demanded by palm oil extraction				WaterPalmOilEx
$WaterPalmOilEx = FWDPE \times PalmOilPr$					
66	Livestock water demand				WaterLiv
$WaterLiv = FLWD \times LivLand$					
67	Population water demand				WaterPop
$WaterPop = FPWD \times PopPalm$					
68	Water demand by biodiesel production				WaterBdPr
$WaterBdPr = FWDBP \times BdPr1G$					
69	Water scarcity index				WaterSI
$WaterSI = \frac{WaterBdSC}{(WaterSup - EcolFl)}$					
70	GHG by oil palm cultivation and palm oil extraction				GHG&POE
$GHG\&POE = BdPr1G \times FGHP\&POE \times EffFactTecPalmOilBd$					
71	GHG Absorption in oil palm cultivation				GHGabs
$GHGabs = LandP_Bd \times FAGHG$					
72	Oil palm cultivation for biodiesel production				LandP_Bd
if ((BdPr1G*EffFactTecPalmOilBd)/CropYieldPalm)<LandP then ((BdPr1G*EffFactTecPalmOilBd)/CropYieldPalm) else LandP					
73	GHG emissions by indirect change of land use				GHGILUC
$GHGinLCBd = GHG\&POE + GHGDLUC + GHGILUC - GHGabs$					
74	GHG emissions by direct change of land use				GHGDLUC
$HGDLUC = Landp_Bd \times [LUCF \times GHGFF + LUCG \times GHGFG + LUCM \times GHGFM + LUCS \times GHGFS + LUCSh \times GHGFSH + LUCW \times GHGFW + LUCB \times GHGFB]$					
75	GHG by biodiesel production and supply chain transport				GHGBdPr&Transp
$GHGBdPr\&Transp = GHGFbDPr\&Transp \times BdPr1G$					

76	GHG emissions in life cycle of biodiesel										GHGinLCBd																																																															
$GHGinLCBd = GHGP\&POE + GHGDLUC + GHGILUC - GHGabs$																																																																										
77	Greenhouse gas Emissions if Diesel 100% is used										GHGifDiesel																																																															
$GHGifDiesel = GHGFLCD \times BdPr1G$																																																																										
78	Percentage GHG emissions saving compared with diesel petrochemical used										%GHGsaving																																																															
$\%GHGsaving = \frac{(GHGifDiesel - GHGinLCBd)}{GHGifDiesel} \times 100$																																																																										
79	Carbon monoxide (CO) emissions of biodiesel blended by diesel										COEmissions																																																															
<p>If time > 8 then [COEmissions = (FCODiesel × DiConsTransp) + FDCO × ((FCODiesel × DiConsTransp) - 1)] else [COEmissions = FCODiesel × DiConsTransp]</p>																																																																										
80	Factor driving CO emissions change										FDCO																																																															
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Polynomial Regression Analysis: FDHC versus MxRtBdDi					
The regression equation is					
FDHC = - 0.003671 - 1.027 MxRtBdDi + 0.3695 MxRtBdDi**2					
S = 0.00610323 R-Sq = 99.9% R-Sq(adj) = 99.9%					
Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	2	0.486920	0.243460	6535.94	0.000
Error	8	0.000298	0.000037		
Total	10	0.487218			
Sequential Analysis of Variance					
Source	DF	SS	F	P	
Linear	1	0.475208	356.11	0.000	
Quadratic	1	0.011712	314.42	0.000	
Final equation: - 0.003671 - 1.027 *MxRtBdDi + 0.3695 *MxRtBdDi ²					

85	Nitrogen oxides (NOx) of biodiesel blended by diesel	NOxEmissions																								
If time>8 then [NOxEmissions=(FNOxDieselxDiConsTransp)+FDNOx*((FNOxDieselxDiConsTransp)-1)] else [NOxEmissions=FNOxDieselxDiConsTransp]																										
86	Factor driving NOx emissions change	FDNOx																								
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FDNOx	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10															
MxRtBdDi	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0															
Regression Analysis: FDNOx versus MxRtBdDi																										
The regression equation is																										
FDNOx = 0.000000 + 0.100 MxRtBdDi																										
Predictor	Coef	SE Coef T P																								
Constant	0.00000000	0.00000000 * *																								
MxRtBdDi	0.100000	0.000000 * *																								
S = 0 R-Sq = 100.0% R-Sq(adj) = 100.0%																										
Final equation: 0.1*MxRtBdDi																										

87	Pollutant Emissions that affect air quality: Biodiesel blend	PEAirQBdDi
If time>8 then [PEAirQBdD=COEmissions+PMEmissions+HCEmissions+NOxEmissions] else [PEAirQBdD=0]		
88	Carbon monoxide (CO) emissions of diesel 100%	COEmissionsDi
OEmissionsDi= FCODieselxDiConsTransp		
89	Particulate matter (PM) emission of diesel 100%	PMEmissionsDi
PMEmissionsDi=FPMDieselxDiConsTransp		
90	Hydrocarbons (HC) emission of diesel 100%	HCEmissionsDi
HCEmissionsDi=FHCDieselxDiConsTransp		
91	Nitrogen oxides (NOx) of diesel 100%	NOxEmissionsDi
NOxEmissionsDi=FNOxDieselxDiConsTransp		
92	Pollutant Emissions that affect air quality: if Diesel 100%	PEAirQifDiesel100%
PEAirQifDiesel100%=COEmissionsDi+PMEmissionsDi+HCEmissionsDi+NOxEmissionsDi		

Table A2-3. Exogenous indicators – Time depend functions

1	Mix ratio biodiesel – diesel	MxRtBdDi																					
<table border="1"> <thead> <tr> <th>Year</th> <th>2008</th> <th>2009</th> <th>2010</th> <th>2011</th> <th>2012</th> <th>2013</th> </tr> </thead> <tbody> <tr> <th>t</th> <td>9</td> <td>10</td> <td>11</td> <td>12</td> <td>13</td> <td>14</td> </tr> <tr> <th>MxRtBdDi</th> <td>0,05</td> <td>0,06</td> <td>0,07</td> <td>0,08</td> <td>0,09</td> <td>0,098</td> </tr> </tbody> </table>			Year	2008	2009	2010	2011	2012	2013	t	9	10	11	12	13	14	MxRtBdDi	0,05	0,06	0,07	0,08	0,09	0,098
Year	2008	2009	2010	2011	2012	2013																	
t	9	10	11	12	13	14																	
MxRtBdDi	0,05	0,06	0,07	0,08	0,09	0,098																	
Data utilized: 2008-2013																							
Regression Analysis: MxRtBdDi versus T																							
The regression equation is																							
MxRtBdDi = - 0.0370 + 0.00971 T																							
Predictor	Coef	SE Coef T P																					
Constant	-0.037048	0.001918 -19.32 0.000																					
T	0.0097143	0.0001650 58.89 0.000																					
S = 0.000690066 R-Sq = 99.9% R-Sq(adj) = 99.9%																							

Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	1	0.0016514	0.0016514	3468.00	0.000
Residual Error	4	0.0000019	0.0000005		
Total	5	0.0016533			

Final equation: $MxRtBdDi = \text{If } (time > 8) \text{ then } (-0.0370 + 0.0097 * time) \text{ else } 0$

Patents biodiesel production first generation

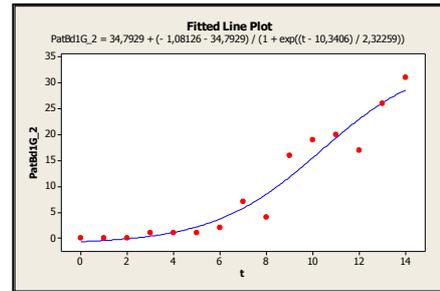
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PatBd1G	0	0	0	1	1	1	2	7	4	16	19	20	17	26	31

Method

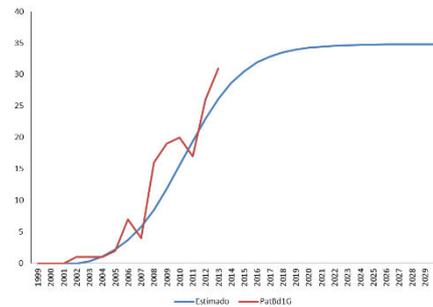
Algorithm Gauss-Newton
 Max iterations 200
 Tolerance 0,00001
 Starting Values for Parameters

Parameter Value
 Theta1 1
 Theta2 1
 Theta3 1
 Theta4 1
 Equation

Parameter Estimates
 Parameter Estimate SE Estimate
 Theta1 34,7929 10,2192
 Theta2 -1,0813 2,2649
 Theta3 10,3406 1,4764
 Theta4 2,3226 1,0188
 $PatBd1G_2 = \text{Theta1} + (\text{Theta2} - \text{Theta1}) / (1 + \exp((t - \text{Theta3}) / \text{Theta4}))$



Summary
 Iterations 50
 Final SSE 98,6545
 DFE 11
 MSE 8,96859
 S 2,99476



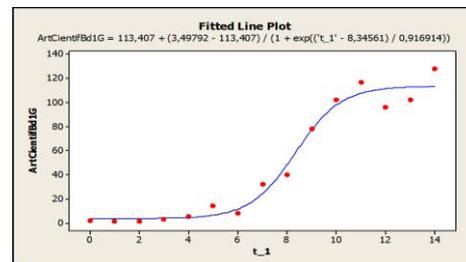
Final equation: $EstPatBd1G = 34,7929 + (-1,08126 - 34,7929) / (1 + \exp((t - 10,3406) / 2,32259))$

Articles of biodiesel production first generation

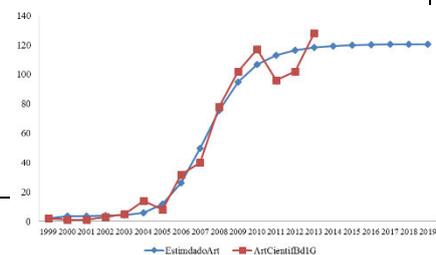
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
ArtCientifBd1G	2	1	1	3	5	14	8	32	40	78	102	117	96	102	128

Algorithm Gauss-Newton
 Max iterations 200
 Tolerance 0,00001
 Starting Values for Parameters
 Parameter Value
 Theta1 1
 Theta2 1
 Theta4 1
 Theta3 1

Parameter Estimates
 Parameter Estimate SE Estimate
 Theta1 120,842 6,41860
 Theta2 3,789 4,42023
 Theta4 7,588 1,75525
 Theta3 8,471 0,29373
 $ArtCientifBd1G = \text{Theta1} + (\text{Theta2} - \text{Theta1}) / (1 + \exp(\text{Theta4} * \ln(t_1' / \text{Theta3})))$



Lack of Fit
 There are no replicates.
 Minitab cannot do the lack of fit test based on pure error.



Summary	
Iterations	25
Final SSE	1036,15
DFE	11
MSE	94,1951
S	9,70542
Final equation:	
ArtCientifBd1G = 120,842 + (3,78856 - 120,842) / (1 + exp(7,58838 * ln('t_1' / 8,47082)))	

CROSS-VALIDATION

The objective of cross validation is to know of if the regression equation structure is capable to predict data that it was considered.

1	Biodiesel production first generation				BdPr1G				
Year		2008	2009	2010	2011				
t		9	10	11	12				
X1-MxRtBdDi		0.05	0.06	0.07	0.08				
X2-Biodiesel production costs - BPC_1G		1185.00	1004.00	1225.00	1409.00				
BdPr1G		22730.00	169411.00	337713.00	443037.00				
Data used: 2008-2011									
First equation: $BdPr1G = -657859,77 + 14690851MxRt - 44,6384614 BPC_1G$									
Resumen									
<i>Estadísticas de la regresión</i>									
Coeficiente de correlación múltiple		0.99659405							
Coeficiente de determinación R^2		0.99319969							
R^2 ajustado		0.97959908							
Error típico		26455.3097							
Observaciones		4							
ANÁLISIS DE VARIANZA									
		<i>Grados de libertad</i>	<i>Suma de cuadrados</i>	<i>Promedio de los cuadrados</i>	<i>F</i>	<i>Valor crítico de F</i>			
Regresión		2	1.0222E+11	5.111E+10	73.0260815	0.08246398			
Residuos		1	699883409	699883409					
Total		3	1.0292E+11						
		<i>Coefficientes</i>	<i>Error típico</i>	<i>Estadístico t</i>	<i>Probabilidad</i>	<i>Inferior 95%</i>	<i>Superior 95%</i>	<i>Inferior 95,0%</i>	<i>Superior 95,0%</i>
Intercepción		-657859.77	111631.512	-5.89313681	0.10700801	-2076272.61	760553.072	-2076272.61	760553.072
Variable X 1		14690851.5	1643005.6	8.94144941	0.07090408	-6185514.08	35567217	-6185514.08	35567217
Variable X 2		-44.6384614	127.664515	-0.34965442	0.78586217	-1666.76992	1577.493	-1666.76992	1577.493
Year	BdPr1G	BdPr1G							
	Real	Predicted	Error						
2012	489991.00	610527.5	24.6						
2013	503337.00	723858.3	43.86						
			34.26						
Year		2010	2011	2012	2013				
t		11	12	13	14				
MxRtBdDi		0.07	0.08	0.09	0.10				
Biodiesel production costs - BPC_1G		1225.00	1409.00	1205.00	1299.00				
BdPr1G		337713.00	443037.00	489991.00	503337.00				
Data used: 2010-2013									
Second equation: $BdPr1G = -204209.699 + 5851503.33 * MxRt + 119.328274 * BPC_1G$									
<i>Estadísticas de la regresión</i>									
Coeficiente de correlación múltiple		0.960375867							
Coeficiente de determinación R^2		0.922321806							
R^2 ajustado		0.766965418							
Error típico		36267.38826							
Observaciones		4							
ANÁLISIS DE VARIANZA									
		<i>Grados de libertad</i>	<i>Suma de cuadrados</i>	<i>Promedio de los cuadrados</i>	<i>F</i>	<i>Valor crítico de F</i>			
Regresión		2	15617658416	7808829208	5.936812882	0.27870808			
Residuos		1	1315323451	1315323451					
Total		3	16932981867						
		<i>Coefficientes</i>	<i>Error típico</i>	<i>Estadístico t</i>	<i>Probabilidad</i>	<i>Inferior 95%</i>	<i>Superior 95%</i>	<i>Inferior 95,0%</i>	<i>Superior 95,0%</i>
Intercepción		-204209.6995	323876.0728	-0.630518018	0.641864778	-4319445.389	3911025.99	-4319445.389	3911025.99
Variable X 1		5851503.33	1723398.691	3.39532771	0.182343125	-16046353.27	27749359.93	-16046353.27	27749359.93
Variable X 2		119.3282741	226.8369325	0.526053111	0.691702737	-2762.908231	3001.56478	-2762.908231	3001.56478
BdPr1G	BdPr1G								

Year	Real	Predicted	error
2008	22730.00	229769.4718	910.8643724
2009	169411.00	266686.0875	57.41958168
			484.141977

Note: in 2008 biodiesel production was started, thus is an atypical biodiesel data. The error will be not considered in final error average

Year	2008	2009	2012	2013
t	9	10	13	14
MxRtBdDi	0.05	0.06	0.09	0.10
Biodiesel production costs - BPC_1G	1185.00	1004.00	1205.00	1299.00
BdPr1G	22730.00	169411.00	489991.00	503337.00

Data used: 2008-2009 and 2012-2013
Third equation: $BdPr1G = -219471.692 + 11184368.1 MxRtBdDi - 270.527578 BPC_1G$

Estadísticas de la regresión	
Coefficiente de correlación múltiple	0.995805596
Coefficiente de determinación R ²	0.991628785
R ² ajustado	0.974886354
Error típico	37870.46678
Observaciones	4

ANÁLISIS DE VARIANZA					
	Grados de libertad	Suma de cuadrados	Promedio de los cuadrados	F	Valor crítico de F
Regresión	2	1.69888E+11	84943847863	59.22848361	0.091494346
Residuos	1	1434172254	1434172254		
Total	3	1.71322E+11			

	Coefficientes	Error típico	Estadístico t	Probabilidad	Inferior 95%	Superior 95%	Inferior 95.0%	Superior 95.0%
Intercepción	-219471.6924	226569.4518	-0.96867292	0.510129542	-3098309.534	2659366.149	-3098309.534	2659366.149
Variable X 1	11184368.1	1253993.853	8.918997543	0.071081091	-4749134.541	27117870.73	-4749134.541	27117870.73
Variable X 2	-270.5275779	235.1024361	-1.150679603	0.455470298	-3257.787265	2716.732109	-3257.787265	2716.732109

	BdPr1G	BdPr1G	
Year	Real	Predicted	error
2010	337713.00	232037.8	31.3
2011	443037.00	294104.4	33.6

Error average of three simulations: 38.1

Conclusions:

- Error average slightly high
- Equation structure are similar in the three simulation. So, equation structure is adequate to use in model and it is possible its use in predicted scenarios.

Used in the model	$BdPr1G = -10099512 * MxRtBdDiesel - 344.4 * BPC_1G$
First simulation	$BdPr1G = -657859.77 + 14690851 * MxRt - 44.6384614 * BPC_1G$
Second simulation	$BdPr1G = -204209.699 + 5851503.33 * MxRt + 119.328274 * BPC_1G$
Third simulation	$BdPr1G = -219471.692 + 11184368.1 * MxRtBdDi - 270.6 * BPC_1G$

25	Crop Yield in Palm Cultivation										CrYieldPalm
Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	
t	0	1	2	3	4	5	6	7	8	9	
CrYieldPalm	4.05	4.09	4.18	3.75	3.58	4.11	4.03	4.02	3.67	3.51	
X1-SoilLossPalm	6038045.6	6331459	6839104.3	7494008.1	8629154.7	10078120.8	11333048.9	12373298.8	13346662.4	14897641.7	
X2-AgrochemPalm	3294830	3433518	3681612	3997136	4549622	5256394	5940594	6436540	6751338	7413032	

Data used: 199 – 2008
First equation:
 $CrYieldPalm = 3.46 - 9.07E-06 * SoilLossPalm + 1.82E-06 * AgrochemPalm$

Estadísticas de la regresión	
Coefficiente de correlación múltiple	0.71
Coefficiente de determinación R ²	0.51
R ² ajustado	0.37
Error típico	0.20
Observaciones	10.00

ANÁLISIS DE VARIANZA				
	Grados de libertad	Suma de cuadrados	Promedio de los cuadrados	Valor crítico de F

Regresión	2	0.275	0.138	3.603	0.084					
Residuos	7	0.267	0.038							
Total	9	0.542								

	<i>Coefficientes</i>	<i>Error típico</i>	<i>Estadístico t</i>	<i>Probabilidad</i>	<i>Inferior 95%</i>	<i>Superior 95%</i>	<i>Inferior 95,0%</i>	<i>Superior 95,0%</i>
Intercepción	3.463	0.491	7.053	0.000	2.302	4.624	2.302	4.624
Variable X 1	0.000	0.000	-1.945	0.093	0.000	0.000	0.000	0.000
Variable X 2	0.000	0.000	1.861	0.105	0.000	0.000	0.000	0.000

Year	Real	Predicted	error
2009	3.41	3.15	7.51
2010	3.00	3.30	9.86
2011	3.54	3.19	9.86
2012	3.25	3.17	2.39
2013	3.11	3.12	0.41
		Average=	6.01

Year	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
t	5	6	7	8	9	10	11	12	13	14
CrYieldPalm	4.11	4.03	4.02	3.67	3.51	3.41	3	3.54	3.25	3.11
SoilLossPalm	10078120.8	11333048.9	12373298.8	13346662.4	14897641.7	16307491.1	18080684.5	19226485.9	20357266.6	21490075.7
AgrochemPalm	5256394	5940594	6436540	6751338	7413032	7931795.1	8890286	9402096.3	9953570	10489204

Data used 2004-2013
Second equation: $CrYieldPalm = 4.21 - 5.18E-7 * SoilLossPalm + 9.58E-07 * AgrochemPalm$

<i>Estadísticas de la regresión</i>	
Coefficiente de correlación múltiple	0.91
Coefficiente de determinación R ²	0.83
R ² ajustado	0.78
Error típico	0.19
Observaciones	10.00

ANÁLISIS DE VARIANZA

	<i>Grados de libertad</i>	<i>Suma de cuadrados</i>	<i>Promedio de los cuadrados</i>	<i>F</i>	<i>Valor crítico de F</i>
Regresión	2.00	1.14	0.57	16.61	0.00
Residuos	7.00	0.24	0.03		
Total	9.00	1.38			

	<i>Coefficientes</i>	<i>Error típico</i>	<i>Estadístico t</i>	<i>Probabilidad</i>	<i>Inferior 95%</i>	<i>Superior 95%</i>	<i>Inferior 95,0%</i>	<i>Superior 95,0%</i>
Intercepción	4.21	0.66	6.40	0.00	2.66	5.77	2.66	5.77
Variable X 1	0.00	0.00	-1.46	0.19	0.00	0.00	0.00	0.00
Variable X 2	0.00	0.00	1.21	0.27	0.00	0.00	0.00	0.00

Year	Real	Predicted	error
1999	4.05	4.24	4.7
2000	4.09	4.22	3.2
2001	4.18	4.19	0.3
2002	3.75	4.16	10.9
2003	3.58	4.10	14.5
		Average=	6.7

Year	1999	2000	2001	2002	2003	2009	2010	2011	2012	2013
t	0	1	2	3	4	10	11	12	13	14
CrYieldPalm	4.05	4.09	4.18	3.75	3.58	3.41	3	3.54	3.25	3.11
SoilLossPalm	6038045.6	6331459	6839104.3	7494008.1	8629154.7	16307491.1	18080684.5	19226485.9	20357266.6	21490075.7
AgrochemPalm	3294830	3433518	3681612	3997136	4549622	7931795.1	8890286	9402096.3	9953570	10489204

Data used: 199-2003 and 2010-2013
Third equation: $CrYielPalm = 4.82 + 3.86E-07 * SoilLossPalm - 9.58E-07 * AgrochemPalm$

<i>Estadísticas de la regresión</i>	
Coefficiente de correlación múltiple	0.89
Coefficiente de determinación R ²	0.79
R ² ajustado	0.72
Error típico	0.22

Observaciones		10						
ANÁLISIS DE VARIANZA								
	<i>Grados de libertad</i>	<i>Suma de cuadrados</i>	<i>Promedio de los cuadrados</i>	<i>F</i>	<i>Valor crítico de F</i>			
Regresión	2	1.227	0.613	12.7	0.00459			
Residuos	7	0.33	0.048					
Total	9	1.56						
	<i>Coefficientes</i>	<i>Error típico</i>	<i>Estadístico t</i>	<i>Probabilidad</i>	<i>Inferior 95%</i>	<i>Superior 95%</i>	<i>Inferior 95,0%</i>	<i>Superior 95,0%</i>
Intercepción	4.83	0.81	5.94	0.00	2.90	6.75	2.90	6.75
Variable X 1	0.00	0.00	0.54	0.61	0.00	0.00	0.00	0.00
Variable X 2	0.00	0.00	-0.62	0.56	0.00	0.00	0.00	0.00

Year	Real	Predicted	error
2004	4.11	3.69	10.3
2005	4.03	3.52	12.7
2006	4.02	3.44	14.3
2007	3.67	3.52	4.1
2008	3.51	3.48	0.7
		Average=	8.5

Error average of three simulations: 7.05

Conclusions:

- Satisfactory error average
- Equation structure are similar in the three simulation. So, equation structure is adequate to use in model and it is possible its use in predicted scenarios.

Used in the model	$CrYieldPalm = 3.7 - 6.5E-7 * SoilLossPalm + 1.28E-6 * AgrochemPalm$
First simulation	$CrYieldPalm = 3.46 - 9.07E-06 * SoilLossPalm + 1.82E-06 * AgrochemPalm$
Second simulation	$CrYieldPalm = 4.21 - 5.18E-7 * SoilLossPalm + 9.58E-07 * AgrochemPalm$
Third simulation	$CrYieldPalm = 4.82 + 3.86E-07 * SoilLossPalm - 9.58E-07 * AgrochemPalm$

Appendix 4. Online survey

<https://docs.google.com/forms/d/1dwBYYCBxFY7ZE7qyA3bgx5joiYhM8PnHAPMHSVQGY/viewform>

Importance of principles and criteria for assessing the sustainability of biodiesel

*** Required**

Introduction

The objective of this research is to evaluate the sustainability of biodiesel. To achieve this, we need to establish the relative importance of the sustainability principles and assessment criteria.

An exhaustive literature review was conducted to identify underlying principles and criteria defined in previous studies. Subsequently, the sustainability vision and a multidimensional perspective of sustainable development was applied in order to propose a hierarchical structure of principles and criteria for evaluating the sustainability of biodiesel chain production (Fig. 1).

Figure 1. Structure model principles and criteria

Purpose of this survey

The purpose of this survey is to collect expert opinions regarding the importance of principles and criteria for sustainability assessment of biodiesel production. In this research, 13 principles and 40 criteria associated with the social, political, economic, technological and environmental sustainability dimension were defined. Below you will find key definitions for some components in the survey:

- Principles:** They are premises, universal bases of fundamentals to define the sustainability of biodiesel production chain.
- Criteria:** They are measurable conditions (qualitative or quantitative) to establish the level of implementation of the sustainability principles in the biodiesel production chain.

The importance of principles and criteria is defined as the level of impact of each criterion and principle in the evaluation of sustainability. It is obtained by weighting the rating given by the experts to each criterion in terms of their relevance, ease of measurement and reliability, which are defined as:

- Relevance:** Measures the level of significance and pertinence of the criterion in the sustainability assessment of biodiesel
- Ease of measurement:** Measures the level of accessibility to information and the ability to perform the measurement of the criterion.
- Reliability:** Measures how credible or certain are the results of the measurement for the criterion.

Based on the given definitions, it is expected that each expert will classify the principles and criteria according to the following scale:

- Null importance: 0
- Low importance: 1
- Moderate importance: 2
- High importance: 3

Expert Information

Name *

Surname *

Area of expertise *

Nationality *

Another nationality, please specify

Name of organization you belong to *

Type of organization *

Continue »

16% completed

Importance of principles and criteria for assessing the sustainability of biodiesel

*** Required**

SOCIAL DIMENSION OF SUSTAINABILITY

Biomass growers and biodiesel processing companies must:

PRINCIPLE 1: Respect property rights, land tenure and customary and traditional rights *
Is Principle 1 important for the sustainability assessment of biodiesel in the social dimension?

0 1 2 3

Null importance High importance

CRITERION 1: Respect the rights of land access and land tenure for peasant and indigenous communities. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 2: Promote the minimization of conflicts over the use, access and land tenure. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Biodiesel production chain must:

PRINCIPLE 2: Be socially acceptable *
Is Principle 2 important for the sustainability assessment of biodiesel in the social dimension?

0 1 2 3

Null importance High importance

CRITERION 3: Contribute to national energy security and the access of rural communities to energy. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 4: To prevent generation of environmental noise. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 5: To prevent changes in landscape generating undesirable visual impacts for communities *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 6: To contribute to local prosperity associated with the reduction of poverty and the promotion of human rights. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Biodiesel production chain must:

PRINCIPLE 3: Promote responsible work conditions through all their activities *

Is Principle 3 important for the sustainability assessment of biodiesel in the social dimension?

0 1 2 3

Null importance High importance

CRITERION 7: Ensure that in all their activities are protecting and promoting workers' occupational safety and health. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 8: To guarantee the respect of labor laws (associated with forced child labor, discrimination, disciplinary practices, working hours, salaries, incidence of occupational accidents, illnesses and deaths, forced and compulsory labor, and unions). *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Biomass cultivation and production of biodiesel must:

PRINCIPLE 4: Prevent alteration to food supply or other local uses of biomass (e.g. energy production, as medicine raw material and as building material) *

Is Principle 4 important for the sustainability assessment of biodiesel in the social dimension?

0 1 2 3

Null importance High importance

CRITERION 9: To prevent alteration to trade and food supply at the local level *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 10: To prevent alteration to biomass production for traditional local uses other than biodiesel (e.g. energy production, as medicine raw material and as building material). *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Are the principles and criteria previously mentioned sufficient to assess the sustainability of biodiesel in the social dimension? *

Are sufficient Are not enough

Principles	<input type="radio"/>	<input type="radio"/>
Criteria	<input type="radio"/>	<input type="radio"/>

Please indicate any other principles or criteria which should be taken into account:

33% completed

Importance of principles and criteria for assessing the sustainability of biodiesel

* Required

POLITICAL DIMENSION OF SUSTAINABILITY

PRINCIPLE 5: National promotion policies for the production and consumption of first generation biodiesel must be in accordance with international policies. *

Is Principle 5 important for the sustainability assessment of biodiesel in the political dimension?

0 1 2 3

Null importance High importance

CRITERION 11: Level of agreement between the amount of biodiesel produced domestically under a subsidy scheme and the one produced internationally under similar schemes. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 12: Level of agreement between domestic "1st-gen./advanced" biodiesel production ratio (defined as (production of first generation biodiesel)/(production of advanced biodiesel)) and international "1st-gen./advanced" ratios *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 13: Level of agreement between the percentages of national biodiesel blend - diesel and percentages of international blend. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 14: Level of national capability in biodiesel research and development (first generation and advanced) regarding international capabilities. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

PRINCIPLE 6. National policies related to the promotion of biodiesel production should be consistent with international environmental policies on acceptable forms of biomass, suitable land for the cultivation of biomass and allowed thresholds of greenhouse gas emissions in the life cycle of biodiesel *

Is Principle 6 important for the sustainability assessment of biodiesel in the political dimension?

0 1 2 3

Null importance High importance

CRITERION 15: Amount of biomass produced domestically in compliance with international standards (type of biomass that does not compete with food). *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 16: National amount of land used for growing biomass for biodiesel production that meets the international requirements of land suitable for use (i.e. those that do not come from direct exchange of primary forests, exclusion areas with high biodiversity value, land with high carbon stocks and ecologically sensitive areas declared as protected). *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 17: Amount of domestically produced biodiesel that meets international policy on minimum average or threshold of greenhouse gas emissions in their life cycle, including indirect changes in land use. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

PRINCIPLE 7: The actors involved in biodiesel's production chain should promote commitment to ethics, transparency and compliance with local laws *

Is Principle 7 important for the sustainability assessment of biodiesel in the political dimension?

0 1 2 3

Null importance High importance

CRITERION 18: Level of perception of the local community about the degree of ethical commitment by the actors in biodiesel's production chain. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 19: Level of perception of the local community about the commitment to transparency and compliance with local laws by the actors involved in biodiesel's production chain. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Are the principles and criteria previously mentioned sufficient to assess the sustainability of biodiesel in the political dimension? *

	Are sufficient	Are not enough
Principles	<input type="radio"/>	<input type="radio"/>
Criteria	<input type="radio"/>	<input type="radio"/>

Please indicate below other principles or criteria which should be taken into account:

50% completed

Importance of principles and criteria for assessing the sustainability of biodiesel

* Required

ECONOMIC DIMENSION OF SUSTAINABILITY

PRINCIPLE 8: Biodiesel production must be sustainable at both macroeconomic and microeconomic level *

Is the Principle 8 important for the sustainability assessment of biodiesel in the economic dimension?

0 1 2 3

Null importance High importance

CRITERION 20: Level of influence (international and domestic) of reserves, production, consumption and prices for oil on the production of first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 21: Level of influence (international and domestic) of production, consumption and prices for diesel on the production of first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 22: Annual production (international and domestic) of first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 23: Level of influence of production, consumption and prices (international and domestic) for vegetable oil on the production of first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 24: Level of influence of production, consumption and prices (international and domestic) for glycerin on the production of first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 25: Level of influence of production, consumption and prices (international and domestic) for advanced biodiesel on first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Are the principles and criteria previously mentioned sufficient to assess the sustainability of biodiesel in the economic dimension? *

	Are sufficient	Are not enough
Principles	<input type="radio"/>	<input type="radio"/>
Criteria	<input type="radio"/>	<input type="radio"/>

Please indicate below other principles or criteria which should be taken into account:

Importance of principles and criteria for assessing the sustainability of biodiesel

* Required

TECHNOLOGICAL DIMENSION OF SUSTAINABILITY

PRINCIPLE 9: Technology used in the biodiesel production chain should promote the reduction of negative impacts on the environment, efficiency and cost reduction in processes over time *

Is Principle 9 important for the sustainability assessment of biodiesel in the technological dimension?

0 1 2 3

Null importance High importance

CRITERION 26: Level of influence of production (international and domestic) of advanced biodiesel from non-edible feedstocks on demand (international and domestic) of soil and water resources. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 27: Level of influence of global and domestic production of advanced biodiesel based on non-conventional technologies on efficiency of processes and cost reduction. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 28: Level of influence of technology trends for engines on the production of first generation biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 29: Level of influence of technological learning (global and domestic) in the production of first generation biodiesel on reducing costs over time. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 29: Level of influence of technological learning (global and domestic) in the production of first generation biodiesel on reducing costs over time. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Are the principles and criteria previously mentioned sufficient to assess the sustainability of biodiesel in the technological dimension? *

	Are sufficient	Are not enough
Principles	<input type="radio"/>	<input type="radio"/>
Criteria	<input type="radio"/>	<input type="radio"/>

Please indicate below other principles or criteria which should be taken into account:

83% completed

CRITERION 31: To promote the efficient use of water to minimize pressure on the local availability of the resource. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 32: To minimize the generation of contaminated effluents and treat such effluents in order to maintain or improve the local water quality. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 33: To ensure that non-hazardous and hazardous wastes are managed responsibly (collection, storage, transportation, treatment and/or disposal) by promoting their minimization, reuse and/or recycling. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 34: The biomass cultivation activities for biodiesel must maintain or improve the soil quality (physical, chemical and biological properties) by establishing responsible practices of crop management, handling of agrochemicals and pest control. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

PRINCIPLE 11: Biodiesel production chain must have a positive balance of greenhouse gases, and maintain or promote carbon sinks *

Is Principle 11 important for the sustainability assessment of biodiesel in the environmental dimension?

0 1 2 3

Null importance High importance

CRITERION 35: The amount of greenhouse gases captured or stored in carbon sinks (biomass associated) must be greater than the amount of greenhouse gases emitted by the biodiesel production chain. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

PRINCIPLE 12: Biodiesel production chain must promote the conservation and protection of biodiversity and wildlife. *

Is the Principle 12 important for the sustainability assessment of biodiesel in the environmental dimension?

0 1 2 3

Null importance High importance

CRITERION 36: Transformation of natural ecosystems and loss of native natural landscape should be avoided during biomass cultivation and biodiesel production. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 37: Biodiesel production chain must preserve areas with fragile ecosystems (both terrestrial and aquatic ecosystems) such as nature reserves defined by the national environmental legislation. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Importance of principles and criteria for assessing the sustainability of biodiesel

* Required

ENVIRONMENTAL DIMENSION OF SUSTAINABILITY

The actors involved in the biodiesel production chain must:

PRINCIPLE 10: Ensure their activities maintain or improve the air, soil and water quality, as well as they do a proper management of solid waste and wastewater *

Is Principle 10 important for the sustainability assessment of biodiesel in the environmental dimension?

0 1 2 3

Null importance High importance

CRITERION 30: To ensure that air quality is maintained or improved. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

PRINCIPLE 12: Biodiesel production chain must promote the conservation and protection of biodiversity and wildlife. *

Is the Principle 12 important for the sustainability assessment of biodiesel in the environmental dimension?

0 1 2 3

Null importance High importance

CRITERION 36: Transformation of natural ecosystems and loss of native natural landscape should be avoided during biomass cultivation and biodiesel production. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 37: Biodiesel production chain must preserve areas with fragile ecosystems (both terrestrial and aquatic ecosystems) such as nature reserves defined by the national environmental legislation. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 38: The number of species of wildlife listed as vulnerable or endangered should not be affected during biomass cultivation and processing of biodiesel. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

PRINCIPLE 13. Energy efficiency and use of renewable energy should be promoted in the processes that are part of the biodiesel production chain. *

Is Principle 13 important for the sustainability assessment of biodiesel in the environmental dimension?

0 1 2 3

Null importance High importance

CRITERION 39: Energy used in the biodiesel production chain from renewable sources. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

CRITERION 40: Energy savings in the biodiesel production chain with compared to the previous year. *

	Null	Low	Moderate	High
Relevance	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Ease of measurement	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reliability	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Are the principles and criteria previously mentioned sufficient to assess the sustainability of biodiesel in the environmental dimension? *

	Are sufficient	Are not enough
Principles	<input type="radio"/>	<input type="radio"/>
Criteria	<input type="radio"/>	<input type="radio"/>

Please indicate below other principles or criteria which should be taken into account:

Importance of principles and criteria for assessing the sustainability of biodiesel

General comments or recommendations:

Dear Expert, thank you very much for your participation and contributions.

Please make sure that your survey was sent successfully, you should see a confirmation page.







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Appendix 5 Technological description of Propanediol production (PDO)

1,3-propanediol (PDO) is a chemical compound belonging to the group of diols. It is used as substrate in many types of synthesis, especially addition polymerization. PDO is traditionally produced by chemical pathway from ethylene oxide in the presence of phosphine, water, carbon monoxide, hydrogen and an acid, or by the catalytic solution phase hydration of acrolein followed by reduction (Adkesson, 2012).

The PDO market in 2014 was \$310.5MM, and it will grow at a compound annual growth rate of 10.4 percent up to \$621MM by 2021 (Markets and Markets, 2015). America dominates the market both in terms of production and consumption. DuPont Tate & Lyle Bio Products Company, LLC is the largest manufacturer of 1,3-PDO and has its plant at Loudon, Tennessee in the U.S., with a production capacity of 63,500.0 tons. In Europe, Middle East and Africa it is expected to grow at the highest growth rate, behaviour that can be attributed to the increasing adoption of bio-based materials in Europe (Markets and Markets, 2015).

As biodiesel industry is rapidly expanding, a glut of crude glycerol is being created, because there is excess of supply and relatively low demand. The price of crude glycerol is very depressed and it is expected to remain low, making it an ideal feedstock for the bio-based chemicals (Ciriminna, 2014). Some studies (Chiu et al., 2006; Knothe, 2010) stated that the production cost of biodiesel was found to vary inversely and linearly with variations in the market value of glycerol (Zheng et al., 2010).

Classical applications of glycerol include personal care products (soaps, cosmetics, hair care, and toothpaste), pharmaceuticals, sweetener in candies and cakes. Additional applications must be explored. These applications imply the production of glycerol esters, glycerol ethers, acetals and ketals, epoxides, aldehydes, ketones, oxidation and dehydration products, as well as 1,2- and 1,3-propanediol (PDO) (Knothe 2010) using glycerol as raw material.

Regarding 1,3-Propanediol, it is copolymerized with terephthalic acid to produce the polyester known as SORONA from DuPont or CORTERRA from Shell. It used in the manufacture of carpets and textile fibers exhibiting unique properties in terms of chemical resistance, light stability, elastic recovery and dyeability (Zimmerman, 1974). Approximately 90% of the total production of 1,3-Propanediol is employed in the production of polytrimethylene teraphthalate (PTT), a polyester traditionally used in textiles. PTT applications have been expanded in recent years to other industries, including consumer products, electronics, and automotive (Molel et

al., 2015). Other polymers produced from PDO include polytrimethylene naphthalate (PTN), polytrimethylene isophthalate (PTI), and thermoplastic polyester elastomer (Molel et al., 2015).

Currently, 1,3-propanediol is produced from petroleum derivatives such as ethylene oxide (Shell route) or acrolein (Degussa-DuPont route) using chemical catalysts (Lam et al., 1997; Arntz et al., 1991). However, it can be produced by alternative routes involving selective dehydroxylation of glycerol through chemical hydrogenolysis or biocatalytic reduction (Zheng, Chen, and Shen 2010).

Chemical catalysts routes

In the presence of metallic catalysts and hydrogen, glycerol can be hydrogenated to 1,2-propanediol, 1,3-propanediol, or ethylene glycol.

- Celanese patented the hydrogenolysis of glycerol water solution under 300 bar of syngas at 200 °C in the presence of a homogeneous rhodium complex [Rh(CO)₂(acac)] and tungstic acid. 1,3-Propanediol and 1,2-propanediol were produced with 20% and 23% yield, respectively (Che, 1987).
- Shell developed the use of homogeneous palladium complex in a water-sulfolane mixture in the presence of methane sulfuric acid. After 10 h of reaction, 1-propanol, 1,2-propanediol, and 1,3-propanediol were detected in a 47:22:31 ratio (Drent and Jager, 1999; Drent and Jager, 2000).
- Schlaf et al., (2001) described the dehydroxylation of glycerol in sulfolane catalyzed by a homogeneous complex of ruthenium. The reaction proceeded under milder conditions (52 bar, 110 °C), but very low yields of 1,2-propanediol and 1,3-propanediol were achieved (<5%).
- Hydrogenolysis on solid catalysts was also attempted. The treatment of glycerol under hydrogen atmosphere in the presence of copper-chromium-based catalysts yielded only 1,2-propanediol (Fleckenstein et al., 1994).
- Montassier et al. (1989), reported that hydrogenolysis of glycerol under 300 bar of H₂ at 260 °C in the presence of Raney nickel, Ru, Rh, and Ir catalysts yielded mainly methane, but in the presence of Raney copper, 1,2-propanediol was the main reaction product.

- Werpy et al. (2002), patented the hydrogenolysis of glycerol and other polyols over Ni/Re catalyst. After 4 h at 230 °C under 82 bar of H₂, 44% of 1,2-propanediol and 5% of 1,3-propanediol were obtained together with 13% of ethylene glycol.
- Glycerol hydrogenolysis on heterogeneous catalysts under 80 bar of H₂ at 180 °C was investigated by Chaminand et al., (2004). Various metals (Cu, Pd, and Rh), supports (ZnO, C, and Al₂O₃), solvents (H₂O, sulfolane, and dioxane), and additives (H₂WO₄) were tested to improve the reaction rate and selectivity. The best selectivity (100%) for 1,2-propanediol was obtained by hydrogenolysis of a water solution of glycerol in the presence of CuO/ZnO catalysts.
- Concerning glycerol hydrogenolysis using Ru/C and an ion- exchange resin (Amberlyst) under mild reaction conditions (120 °C, 80 bar) (Furikado et al., 2007).
- Hydrogenolysis of glycerol with various SiO₂ supported noble metal catalysts has been studied (Furikado et al., 2007). Rh/SiO₂ is effective in the reaction of glycerol under H₂ atmosphere. It was found that Rh/SiO₂ exhibited higher activity and selectivity to hydrogenolysis products in the reaction of glycerol than the conventional catalyst Ru/C. In particular, under higher H₂ pressure and higher concentration of glycerol, Rh/SiO₂ was much more effective than Ru/C. The consecutive hydrogenolysis of propanediols to propanols in the glycerol reaction can proceed mainly via 1,3-propanediol on Ru/C, while the consecutive reactions can proceed mainly via 1,2-propanediol on Rh/SiO₂.

Selective Dehydroxylation

Wang et al. (2003), reported a new approach to the production of 1,3-propanediol from glycerol via selective dehydroxylation. The concrete process is to selectively transform the middle hydroxyl group of glycerol into a tosyloxyl group and then remove the transformed group by catalytic hydrogenolysis. The reaction consists of three steps: acetalization, tosylation, and detosyloxylation. The aim is to selectively transform the second hydroxyl group of glycerol into a tosyloxyl group (tosylation) and then remove the tosyloxyl group by catalytic hydrogenolysis (detosyloxylation). As compared to the hydroxyl group, the tosyloxyl group is a better leaving group and is easier to replace with a hydride ion.

The first step in the conversion of glycerol to 1,3-propanediol is to acetalize the glycerol with benzaldehyde. The purpose is to protect the first and third hydroxyl groups of glycerol, so that only the middle one can be tosylated in the second step and subsequently removed in the third step. The condensation between glycerol and benzaldehyde is an equilibrium reaction, but it

can be driven to completion by removing the water formed in the reaction. The second step of the conversion is tosylation of the unprotected hydroxyl group of the acetalized glycerol, so as to transform it into a good leaving group. This step is a fairly straightforward process. The final step of the conversion is a detosyloxylation reaction preceded or followed by a hydrolysis reaction. The detosyloxylation reaction removes the tosylated middle hydroxyl group, while the hydrolysis reaction removes the protection on the first and third hydroxyl groups. According to the proposed conversion approach, this reaction is to be done with molecular hydrogen in the presence of a transition metal catalyst.

Biocatalysts

Microbial production of 1,3-propanediol has been widely researched and considered as a competitor to the traditional petrochemical routes (Zheng et al., 2010). It is an example of a socially beneficial method for obtaining bulk chemicals from renewable resources (Zheng et al., 2010). Only a small number of microorganisms in nature are able to produce 1,3-propanediol via glycerol fermentation, including *Klebsiella pneumoniae* (Petitdemange et al., 1995; Mu et al., 2006; Cheng et al., 2006), *Enterobacter agglomerans*, *Citrobacter freundii*, *Clostridium acetobutylicum*, *Clostridium butyricum* (Petitdemange et al., 1995; Zeng, 2006), *Clostridium pasteurianum*, *Lactobacillus brevis*, and *Lactobacillus buchneri* (Talarico et al., 1990; Veiga-da-Cunha et al., 1992). Among them, more attention has been directed at *K. pneumoniae*, *C. freundii*, and *C. butyricum* because of their appreciable substrate tolerance, yield, and productivity.

Biosynthesis of 1,3-propanediol under anaerobic conditions takes place via the following biochemical reactions:

- Some of the glycerol is oxidized to dihydroxyacetone by an NAD-dependent glycerol dehydrogenase, while the remainder is dehydrated to 3-hydroxypropionaldehyde by a vitamin B12-dependent dehydratase. The product of the dehydration reaction, 3-hydroxypropionaldehyde, is reduced to 1,3-propanediol by an NAD-dependent oxidoreductase. In this case, the final acceptor of the electrons is the 3-hydroxypropionaldehyde. However, several studies found that 3-hydroxypropionaldehyde would inhibit 1,3-propanediol synthesis (Schuetz et al., 1984; Barbirato et al., 1998)

On the other hand, recovering and purification of 1,3-propanediol from the fermentation broth is a complex task because of both its high hydrophilic character and its high boiling point (Posada et al., 2013).

Discussion

Chemical synthesis of PDO has numerous disadvantages, including many byproducts, poor selectivity, high temperature and pressures required for operation, expensive catalysts, and cause the release of environmentally toxic intermediate compounds (Da Silva et al., 2009; Liu, 2013). The biocatalyst is a promissory process that uses a renewable source, glycerol, as feedstock, prevent toxic byproducts. This process is used in industrial application, for example, the joint venture between DuPont and Tate & Lyle commercialized the large-scale industrial fermentation to produce bio-based PDO. Therefore, biocatalyst process is considering to be applied in the valorisation of glycerol, due the glycerol production linked to Colombian biodiesel production.

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ÉVALUATION DE LA DURABILITÉ DE LA PRODUCTION DU BIODIESEL EN COLOMBIE

Résumé

Évaluation de la durabilité de la production de biodiesel est un sujet d'importance croissante en raison de l'intérêt des gouvernements à effectuer des stratégies de souveraineté, diversifier leur matrice énergétique et mis en place l'impact de la production de biocarburants. Dans ce contexte, ce travail propose un modèle dynamique du système pour évaluer la production de biodiesel dans un contexte spécifique, basé sur une structure hiérarchique générale d'évaluation de la durabilité qui intègre les dimensions du développement durable avec les principes, critères et indicateurs (PC & I). Le cadre de l'évaluation de la production de biodiesel a été défini d'après une ample état de la technique, ce qui entraîne une sélection et analyse de 113 documents, y compris les lois, directives et autres documents normatifs, les documents de politique, les certificats et documents publiés dans des revues. Pour définir le cadre final, une stratégie de validation basée sur les consultations d'experts enquête et une analyse statistique descriptive a été réalisée. Ainsi, un cadre composé de cinq dimensions (sociales, économiques, environnementale, politiques et technologiques), 13 principes et 31 critères a été proposé.

Par la suite, un modèle de dynamique de système (DS) a été développé et appliqué pour évaluer la durabilité de la production du biodiesel en Colombie. Au départ, le modèle DS a été utilisé pour simuler la production du biodiesel, compte tenu des conditions actuelles en Colombie, ce qui permet de déterminer le niveau de référence (années 2008-2014). Par la suite, certains indicateurs exogènes du scénario de référence ont été modifiés afin de générer une analyse de sensibilité pour définir plusieurs conditions fondamentales vers la production de biodiesel durable dans le contexte colombien. Une fois l'analyse de sensibilité a été réalisée, on a déterminé les conditions qui favorisent ou découragent la production de biodiesel et, par conséquent, des scénarios optimistes et pessimistes ont été proposées. Les résultats de l'analyse des scénarios peuvent aider les institutions, les décideurs et les autres parte prenants associés à établir les conditions à réaliser pour promouvoir une production durable du biodiesel.

Mots clés: Évaluation de la durabilité, Production du biodiesel, dynamique des systèmes

SUSTAINABILITY ASSESMENT OF BIODIESEL PRODUCTION IN COLOMBIA

ABSTRACT

Sustainability assessment of biodiesel production is a topic of increasing importance due to the interest of governments to stablish sovereignty strategies, diversify their energy matrix and set up the impact of biofuels production. In this context, this work proposes a system dynamic model to assess biodiesel production in a specific context, based on a general hierarchical structure of sustainability assessment that integrates dimensions of sustainable development with principles, criteria and indicators (PC&I). The assessment framework of biodiesel production was defined based on a comprehensive state of the art, resulting in a selection and analysis of 113 documents, including laws, directives and other normative documents, policy documents, certificates and papers published in peer-reviewed journals. To define the final framework, a validation strategy based on expert survey consultations and a descriptive statistical analysis was conducted. As a result, a framework composed of five dimensions (social, economic, environmental, political and technological), 13 principles and 31 criteria was proposed.

Subsequently, a System Dynamics (SD) model was developed and applied for assess the sustainability biodiesel production in Colombia. Initially, the SD model was used to simulate the biodiesel production considering the current conditions in Colombia, enabling to determine the baseline (years 2008 to 2014). Subsequently, some exogenous indicators of the baseline scenario were modified in order to generate a sensibility analysis to define several fundamental conditions for the sustainable biodiesel production in the Colombian context. Once the sensibility analysis was conducted, the conditions that promote or discourage biodiesel production were determined and, consequently, optimistic and pessimistic scenarios were proposed. The results of the analysis of the scenarios can help institutions, decision-makers and other agents related to establish the conditions to be carried out to promote a sustainable biodiesel production.

Keywords: Sustainability assessment, biodiesel production, system dynamics