IMPACT OF BIOFUELS PRODUCTION ON LAND-USE CHANGE AND GREENHOUSE GAS EMISSIONS
Methodological framework and system dynamics modeling applied to soybean-based biodiesel production in Argentina

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y Abstract

This research assesses the effect of greenhouse gas (GHG) emission constraints imposed in biofuel importing countries on the export potential of biofuel producing countries. Several countries are promoting the introduction of biofuels on their energy matrix through ambitious biofuel mandates but also specify a certain level of GHG emission reduction that biofuels should fulfil. Biofuel producing countries focused on the international market should comply with this criterion in order to supply biofuels to those countries. Biofuel producers should then report the GHG emission saving (GES) of the biofuel they supply. A critical issue in this assessment is the inclusion of GHG emissions from land-use change (LUC) induced by the production of feedstock for biofuels.

Focusing on the Argentinean case, this thesis analyses the soybean-based biodiesel export potential of Argentina to the European Union (EU), including the GES threshold imposed in the EU Renewable Energy Directive (RED). The thesis therefore focuses on estimating the biofuel GES based on the impact of soybean production on direct land-use changes (dLUC) at the country level. Key factors influencing this result include the policy framework regulating the biofuel supply chain, the evolution of prices and demand for soybean-based products and the feedstock production patterns. The thesis proposes a modeling approach to assess the effect of these factors on soybean-based biodiesel production and exports.

The approach is based on a market analysis of soybean and of higher value-added products, a conceptual modeling framework and a simulation model. The market analysis serves as a background study to define the modeling foundations. The conceptual modeling framework specifies the main interaction among producers in the biodiesel supply chain and their link to international markets, land-use changes and GHG emissions. Simulations are then performed to assess how those key factors affect the Argentinean (AR) biodiesel export potential to the EU. To this end, a system dynamics simulation model is developed. The simulation model includes a life cycle assessment model used to estimate the biofuel GES.

The research explicitly addresses the allocation of biodiesel production between two types of producers and two market destinations, provided that specific policies regulate the domestic biodiesel industry. Land supply for soybean production is estimated based on the evolution of demand for soybean, competing and higher value-added products. Dynamics in the international markets are addressed through a scenario-based approach to define a plausible scenario of the market evolution. Feedstock production patterns are accounted for by disaggregating soybean production in four different regions (Centre, South-East, North-East and North-West). In each region, the expansion of managed lands is modeled based on the current share of three soybean cultivation methods and seven unmanaged land types. The biofuel GES is finally compared with the EU-RED GES threshold to estimate the biofuel export potential under GHG emission constraints.

Results indicate that the impact of biodiesel production on soybean land supply was small compared with the effect of soybean oil and meal exports. While biodiesel production affects mainly soybean oil exports, this effect is still marginal given the biodiesel production level and the economic value attached to soybean meal for the given scenario. Land supply for soybean production therefore seems to depend more on how Argentinean soybean meal exports affect the price of soybean in the international market. Despite the large share of Argentina in the soybean meal export market, this market is likely to be competitive.

Biodiesel domestic policy instruments significantly affect the biodiesel export potential, especially when different domestic blending targets are applied. With respect to the national biodiesel mandate large firms are mainly export oriented while small and medium firms exclusively supply the domestic market. Moreover, export taxes seemed to significantly affect the biodiesel export potential through its direct effect on producer profits.

Feedstock production patterns largely influence dLUC from soybean production. The supply of cropland for soybean cultivation differs among regions. Higher land productivities and the application of first-occupation no-tillage farming in the Central region led to higher net returns to land and lower land requirements. Soybean cultivation in the Central region leads mainly to displacement of other crops and pastures, given constraints in land availability. Cropland supply in other regions resulted in higher dLUC due to lower land productivities and the application of conventional tillage that lead to lower yields. In the South-East and North-East regions cropland expanded mainly into mixed land, grassland and shrubland. In the North-West region, cropland expansion into forests resulted in significant GHG emissions from dLUC.

The allocation of dLUC from cropland expansion to biodiesel resulted in different biodiesel export potentials. Producers located in the C region seemed to be those with the highest potential for exporting biodiesel, given their higher profits and higher GES compared with other regions. Producers in the C region can supply biodiesel to the export market with a GES of 45% complying with the EU-RED GES threshold, at least until 2017. If no dLUC occurs, the GES for biodiesel produced in this region rises to 57%. Supply by other regions to the international market is constrained by the non compliance with the GES threshold.

Perspectives for further research include additional simulations to assess the biofuel GES and the export potential under other market scenarios and policy contexts. The modeling framework may be extended to the individual producer level and may also be linked to a global approach to improve the modeling of market interactions in the world economy and the accounting of indirect land-use change. Finally, the extension to geographic information systems (GIS) can improve the representation of land heterogeneity and the induced land-use changes from soybean production.

Key words: Biofuels, land-use change, greenhouse gas emissions, export potential.

y Résumé

Cette recherche évalue le potentiel d'exportation de biocarburant des pays producteurs pour le marché international, en fonction des contraintes liées aux critères de réduction d'émissions des gaz à effet de serre (GES) imposés dans les pays importateurs. Plusieurs pays encouragent l'introduction des biocarburants dans leur système énergétique à travers des mandats ambitieux et imposent également une réduction minimale des émissions de GES pour les biocarburants. Les pays exportateurs doivent respecter cette contrainte. En particulier, l'évaluation de ces derniers doit inclure le changement d'affectation des terres (CAT).

Axé sur le cas argentin, cette thèse analyse le potentiel d'exportation du biodiesel à base de soja, à destination de l'Union Européenne (UE), en tenant compte du seuil imposé par la directive européenne sur les énergies renouvelables (RED) sur la réduction des émissions de GES (REG). Cette recherche évalue les émissions de GES en fonction du CAT en Argentine pour la production de biodiesel a partir de soja; les principaux facteurs étant le cadre politique, l'évolution des prix et des demandes de produits à base de soja et les modes de production de la matière première. La thèse propose une approche modélisée pour évaluer l'effet de ces facteurs sur la production et l'exportation du biocarburant.

La méthodologie est basée sur i. une analyse du marché de soja et des produits à plus forte valeur ajoutée, ii. un cadre conceptuel de modélisation et iii. un modèle de simulation. L'analyse du marché sert de base pour définir l'environnement du modèle. Ce dernier précise les principales interactions au sein de la filière du biodiesel ainsi que son lien avec le marché international, le CAT et les émissions de GES. Des simulations sont ensuite effectuées pour évaluer le rôle de ces facteurs sur les exportations de biodiesel argentin pour l'UE. À cette fin, un modèle de simulation dynamique est développé. Ce dernier inclut un modèle d'analyse du cycle de vie, utilisé pour estimer le potentiel de REG du biodiesel.

Cette recherche traite différemment la production de biodiesel selon les types de producteurs et de marchés. Des politiques spécifiques régulent l'industrie nationale de biodiesel. L'allocation des terres pour la production de soja est estimée en tenant compte des demandes additionnelles pour l'exportation d'huile et de tourteau de soja. Une approche par scénarios est utilisée pour simuler l'évolution du prix et de la demande de soja, des produits concurrents et des produits à plus forte valeur ajoutée. Les modes de production de soja sont comptabilisés dans quatre régions de production (Centre, Sud-est, Nord-est, Nord-ouest). Dans chacune, l'expansion des terres cultivées, se poursuit selon la répartition actuelle de types des terres et des méthodes de production. Le potentiel de REG du biodiesel dans chaque région est finalement comparé au seuil imposé par l'UE pour estimer le potentiel d'exportation du biocarburant en respectant la directive RED.

Les résultats indiquent que l'impact de la production de biodiesel sur l'allocation des terres est faible par rapport à celui lié aux exportations d'huile et du tourteau de soja. La production de biodiesel influence principalement les exportations d'huile de soja. Cependant, cet effet est encore marginal étant donné le faible niveau de production de biodiesel et l'importante valeur économique du tourteau de soja pour le scénario retenu. L'occupation des terres pour la production de soja semble donc dépendre davantage de la façon dont le prix du soja sur le marché international est affecté par la demande en tourteau. Malgré la part de marché importante de l'Argentine dans les exportations mondiales du tourteau de soja, ce marché est susceptible d'être compétitif.

Les instruments de la politique nationale du biodiesel influencent de façon importante le potentiel d'exportation du biodiesel, surtout lorsque différents objectifs de mélange de biodiesel et diesel fossile sont appliqués sur le marché intérieur. Compte tenu du quota réservéé aux petites et moyennes entreprises pour l'approvisionnement du marché intérieur, les grandes entreprises sont principalement orientées vers l'exportation. Par ailleurs, les taxes d'exportation affectent de manière significative le potentiel d'exportation du biodiesel à cause de leur effet direct sur les profits des producteurs.

En outre, les méthodes de production de soja influent largement sur le CAT. L'allocation des terres agricoles pour la culture du soja varie selon les régions. Dans la région Centre, la meilleure productivité des terres et la culture du soja en première occupation et sans labours conduisent à des rendements élevés. L'expansion de la culture du soja dans la région Centre résulte principalement dans un déplacement des autres cultures et des prairies sylvo-pastoraux, compte tenu des contraintes de disponibilité de terre. L'occupation des terres cultivées dans d'autres régions entraîne un important CAT en raison des productivités plus faibles et de l'application du labour conventionnel. Dans les régions Sud-est et Nord-est l'expansion des terres cultivées se fait en détriment des terres mixtes, des prairies de pâturage libre et des terres arbustives. Dans la région Nord-ouest, l'expansion des terres cultivées sur la forêt entraîne d'importantes émissions de GES.

L'assignation au biodiesel du changement direct d'affectation des terres entraîne différents potentiels d'exportation. Les producteurs situés dans la région centrale semblent être ceux qui bénéficient du plus grand potentiel pour l'exportation étant donnés leurs profits et leur potentiel de REG plus élevé par rapport aux autres régions. Les producteurs de la région Centre peuvent fournir du biodiesel pour l'exportation avec une REG de 45% conforme au seuil de la RED, au moins jusqu'en 2017. Si aucun changement direct d'affectation des terres ne survient, la REG pour le biodiesel produit dans cette région s'élève à 57%. L'approvisionnement du biodiesel par d'autres régions pour le marché international est limité par la non conformité avec le seuil de REG.

Les perspectives de recherche envisagent des simulations supplémentaires pour évaluer la REG du biocarburant et le potentiel d'exportation selon d'autres contextes politiques et d'autres scenarios. Le cadre de modélisation peut être étendu au niveau du producteur individuel et peut également être lié à une approche globale pour améliorer la modélisation des interactions avec le marché international et la comptabilisation des effets indirects sur le CAT. Enfin, le recours aux systèmes d'information géographique (SIG) peut améliorer la représentation de l'hétérogénéité des terres et le CAT induit par la production de soja.

Mots clés: biocarburants, changement d'affectation des terres, émissions de gaz à effet de serre, potentiel d'exportation.

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AR	Argentinean
BM	Biodiesel market
BX	Biodiesel X% volumetric blend
C	Central soybean supply region
CD	Crushing dynamics
CET	Constant elasticity of transformation
CLD	Causal Loop Diagram
DET	Differential export tax
dLUC	Direct land-use change
EU	European Union
FAO	United Nations Food and Agricultural Organisation
FAPRI	Food and Agricultural Policy Research Institute
font	First occupation no-tillage
foct	First occupation conventional tillage
GES	Greenhouse gas emission saving
GHG	Greenhouse Gas
iLUC	Indirect land-use change
LCA	Life Cycle Assessment
LCS	Land competition and supply
LUC	Land-Use Change
NE	North-Eastern soybean supply region
NO	North-Western soybean supply region
OECD	Organisation for Economic Co-operation and Development
RED	Renewable Energy Directive
SD	System Dynamics
SE	South-Eastern soybean supply region
SFD	Stock and Flow Diagram
s&m	Small and medium firm
sont	Second occupation no-tillage

> *“We need to be concerned about the possibility of taking land or replacing arable land because of these biofuels. Just criticizing biofuel may not be a good solution. We need to address these issues in a comprehensive manner."*
>
> Ban Ki-moon- UN General Secretary

> *“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.”*
>
> Sir William Bragg

> *"Everything should be made as simple as possible, but not simpler."*
>
> Albert Einstein

1. Introduction

1.1. Background for the study

1.1.1. GHG emissions restriction for biofuels supply

Worldwide concerns about the depletion of non-renewable fossil fuels and the global warming effect have underpinned biofuels demand in the last few years (Demirbas 2009). Encouraged by political support, biofuels demand has largely been on the increase in some countries as a substitute for fossil fuels (Charles *et al.* 2007). World biodiesel demand, for instance, was 7.8 Mton/year in 2006, increased to 19.8 Mton/year in 2010 and projections for 2020 state biodiesel demand will grow to 41.9 Mton/year, following ambitious biodiesel policies being implemented mainly in developed countries (OECD-FAO 2010).

Biofuels trade, on the other hand, has also increased in recent years. Structural factors constraining supply in consuming countries mainly lead to biofuel imports in order to satisfy domestic biofuel mandates (Ponti and Gutierrez 2009). Therefore, some countries with competitive advantages for biofuels production have encouraged the development of the biofuel industry for the export market, mainly based on the utilisation of food crops (first generation biofuels) (Sorda *et al.* 2010). World biodiesel exports, for instance, were almost zero in 2006, increased to 1.9 Mton/year in 2010 and are projected to increase to 2.7 Mton/year by 2020 (OECD-FAO 2010).

Concerns about biofuels sustainability have also increased worldwide, pushing governments and international agencies to develop sustainability criteria for biofuels that producers must respect (van Dam *et al.* 2010). Among these criteria, special attention has been put on reporting the greenhouse gas (GHG) emission saving (GES) of biofuel (Panichelli and Gnansounou 2008). Several initiatives including, for example, the Renewable Transport Fuel Obligation (RTFO) in the United Kingdom, the Renewable Energy Directive (RED) in the European Union (EU), the Low-Carbon Fuel Standard (LCFS) in the State of California and the EPAs’ Renewable Fuel Standard (RFS2) in the United States (US) mandates report the GHG emission performance[1] of the produced biofuel (CARB 2009; EC 2009; EPA 2010a).

To this end, biofuel producing countries focused on the export market should assure that the biofuel they supply to those markets complies with the GHG emission restrictions imposed in the importing country. The development of the biofuel industry will be subjected to the ability of producers to deliver biofuels that respect this compulsory sustainability criterion.

One of the major issues of discussion in the assessment of the biofuel GES is the impact of the feedstock production phase on land-use change (LUC) (Fargione *et al.* 2008; CBES 2009). When land-use changes occur, the GES of the biofuel may be offset by the direct or indirect contribution to carbon stock changes in land (Righelato and Spracklen 2007). Some recent studies evidence the significance of LUC on biofuels GHG emission balances (Johansson and Azar 2007; Keeney and Hertel 2008; Panichelli and Gnansounou 2008; Searchinger *et al.*

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[1] The measure of the GHG emission performance varies among regulations.

2008; Kim *et al.* 2009; Melillo *et al.* 2009; Lapola *et al.* 2010; Banse *et al.* 2011). While quantitative estimations of GHG emission from LUC vary significantly (Edwards *et al.* 2010b), a critical issue for biofuel producers focused on the international market is the impact of these emissions on fulfilling the GES threshold imposed in importing countries.

1.1.2. Argentinean potential as a biodiesel exporter to the European Union

The EU and Argentina (AR) are projected to be the two main market players in the international market of biodiesel (Figure 1-1). While the EU accounts for almost the totality of biodiesel imports, Argentina is the main biodiesel exporter.

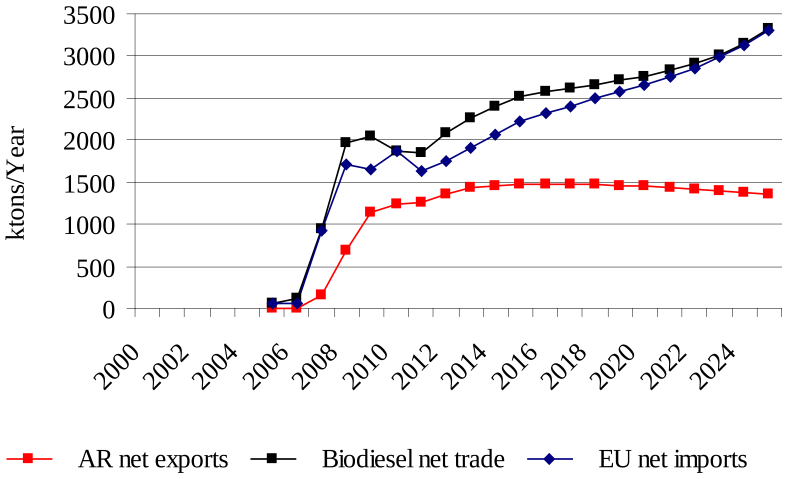

Figure 1-1. Biodiesel trade: AR exports and EU imports.

Sources: FAPRI (2010b) and OECD-FAO (2010).

Several reasons have made the EU the first world biodiesel importer. Firstly, the EU has set ambitious blending targets to introduce biofuels in the transport sector. The EU-RED mandates a 10% blending target for biofuels in the transport sector by 2020 (EC 2009). Biodiesel is expected to account for 80% of the total amount of biofuels to be supplied (EC 2005). Provided that the EU is the first biodiesel producer in the world, a significant amount of this biodiesel is expected to be supplied by domestic firms. For instance, EU biodiesel production was 12.3 Mton/year in 2010 and is expected to increase to 15.1 Mton/year by 2020 (FAPRI 2010b).

While the EU accounts for a significant part of the biodiesel installed capacity in the world (21 Mton/year), utilisation rates are low, averaging 43% (CADER 2011). Moreover, land availability constraints for rapeseed cultivation also limit domestic biodiesel production. Therefore, it can be expected that EU biodiesel production will be insufficient to satisfy the blending obligations imposed in the EU-RED, leading to a potential increase in biodiesel imports by EU member countries. In 2010, for instance, the EU imported 15% of biodiesel and this trend is expected to continue in the next few years, reaching 18% in 2020 (FAPRI 2010b; CADER 2011).

On the other hand, significant investments have been done in the Argentinean biodiesel sector over the last few years that have led to the development of a growing domestic biodiesel industry. Argentina has been ranked as the third country in the world with the highest potential for biodiesel production (Johnston and Holloway 2007). Moreover, the country is currently the first world biodiesel exporter and projections indicate that this trend will continue in the future (FAPRI 2010; OECD-FAO 2010).

Argentinean biodiesel is mainly produced from soybeans. In the Argentinean case, soybean represents 53% of the country's cultivated area with grains, and 88% of this surface is concentrated in the central region of the country, representing 83% of national soybean production (INDEC 2002). The competitive advantage of the country as a soybean-based biodiesel exporter relies mainly on the economic efficiency of its soybean sector (USDA 2001) that led the country to become the first exporter of soybean oil and meal and the third largest soybean producer in the world (OECD-FAO 2010). Biodiesel production from this source is expected to significantly increase in the upcoming years, mostly for the international market (van Dam *et al.* 2009a).

Argentina is expected to be a main European partner in biodiesel trade (FAPRI 2010b). In 2011, the main destinations of Argentina biodiesel exports were mainly Italy, Spain and the Netherlands (CADER 2011), reflecting the trade linkage between Argentina and the EU. Biodiesel trade with the EU however is subjected to the respect of sustainability criteria. Article 17 of the EU-RED defined sustainability criteria for biofuels, irrespective of whether the raw material is cultivated inside or outside the EU. Among these criteria, the EU-RED requires that the GHG emission saving (GES) from the use of biofuels shall be at least 35%. This threshold increases to 50% by January 2017 and to 60% after January 2018.

The biofuel GES is estimated as the percentage reduction in GHG emissions between the biofuel and its fossil fuel reference. The EU-RED give default and typical values of GES to help producers reporting the GES of their biofuel pathway. In the case of soybean-based biodiesel, default and typical values are 31% and 40%, respectively (EC 2009), meaning that if typical values are assumed, soybean-based biodiesel does not respect the EU-RED GES threshold. These values however are based on average data that in some cases does not reflect the regional specificities from where the biofuel is produced, and moreover, they do not account for land-use change emissions. Consequently, several countries are engaged in assessing the biofuel GES including these specific conditions. In the Argentinean case, some studies have already been performed for this purpose. The treatment of GHG emissions from LUC however remains a controversial issue.

The biodiesel GES depends largely on the agricultural phase and especially on LUC induced by the feedstock production for biofuels. Several studies show the significant impact of soybean production as a driver of land-use change, mainly as a contributor to deforestation processes in dry subtropical forests in Northern Argentina (Pengue 2003; Grau *et al.* 2008; Galligani 2009) and the displacement of pastures and other crops in the central region (Martellotto *et al.* 2001; Pengue 2003; Henry *et al.* 2009; OEA 2009). According to van Dam *et al.* (2009b) for instance, GHG emissions from soybean production account for 75% of the biodiesel life cycle GHG emissions. Moreover, Panichelli *et al.* (2009) report that land-use change represents 77% of the GHG emissions of soybean-based biodiesel production in Argentina. Therefore land-use change emissions are expected to significantly affect the Argentinean biodiesel export potential.

To conclude, biodiesel exports from Argentina to the EU are expected to be significant, given both supply constraints in EU member countries and ambitious production plans of the Argentinean biodiesel industry with a focus on the export market. Biodiesel trade however, will be subjected to the compliance of the GES threshold imposed in the EU-RED. In this context, the effect of land-use change GHG emissions can play a major role in fulfilling the biodiesel GES threshold.

1.2. Problem definition: Biodiesel exports and GHG emission restrictions

Investments in the biofuel industry, especially in some developing countries, are being done with the expectation that production will be sold in the international market. The access to this market however partly depends on the ability of producers to deliver biofuels that respect sustainability criteria and particularly GHG emissions restrictions. From a planning perspective, it becomes essential to assess the biofuel export potential accounting for this constraint. Performing this task entails mainly the estimation of the biofuel GES and the assessment of critical factors affecting the fulfilment of GHG emissions restrictions.

A critical factor affecting the biofuel GES are GHG emissions from land-use change. LUC GHG emissions depend mainly on the supply of land for the feedstock production and the type of converted land-use. In the case of first generation biofuels, crops used as feedstock for biofuels production also have distinct demand drivers. Biofuels currently account for a small share of the demand for these crops. In this case, land supply for feedstock production is mainly driven by the demand of crops for other purposes. Land supply in this context is linked to the characteristics of the whole agricultural system in which the feedstock is produced. These characteristics include, among others, biophysical factors constraining land supply, land-use expansion patterns, feedstock cultivation methods and techno-economic and political factors affecting producer profits. Consequently, providing the biofuel GES relied mainly on the agricultural phase, a proper assessment of the export potential would imply assessing the effect of these factors on the biofuel GES.

The problem tackled in the research can be expressed based on the following questions:

§ How do international market dynamics affect supply of soybean products?

§ How do governmental policies affect supply of soybean products?

§ How soybean production patterns affect the biodiesel GES?

§ Which is the biodiesel export potential under GHG emission constraints?

In the case of soybeans, demand is mainly driven by the derived demand for soybean value-added products, namely, soybean oil and meal. Consequently, land supply for soybean production depends mainly on the market dynamics of both products. In the Argentinean case, besides a limited quantity of soybean directly exported as grain, soybeans are mainly domestically crushed into soybean oil and meal. These products have been historically produced for the international market. Provided that Argentinean soybean land supply depends on the international market dynamics for soybean products it becomes essential to assess its effect on the biodiesel export potential.

Secondly, a key feature of current biofuels policy is the combination of instruments supporting the supply and demand side of the biofuel sector. Moreover, due to the combined characteristics of biofuels as a substitute to fossil fuel, an environmental good and an agricultural-based product, biofuel policies are generally linked with energy, environmental and agricultural policies that frame the policy context in which the domestic biofuel industry is developed. These policies regulate the ability of producers to supply feedstock, intermediate products and biofuels to the market. The resulting quantity of soybean-based biodiesel supplied to the international market by Argentinean producers will, therefore, depend on the policy framework affecting the biodiesel supply chain.

Finally, a critical factor to be considered is the production patterns in the feedstock production phase. Production patterns may differ depending on the location from where the feedstock is supplied. Biophysical factors such as land availability and productivity, for instance, may constrain land supply for soybean production in different locations. Moreover, soybean cultivation methods and land-use expansion patterns can also differ among locations. For instance, if soybean production expands into high carbon stock lands, land-use change emissions may increase, reducing the GES. In this case, if the GES of the biodiesel is higher than the threshold imposed by the EU-RED, the biodiesel export potential may be reduced.

1.3. Objectives and scope of the research

This research aims to assess the biofuel export potential of a country under GHG emission constraints imposed in biofuel importing countries. This thesis tackles the effect of the GES threshold imposed in the EU-RED to supply biofuels to the European market. A decisive factor influencing the fulfilment of this criterion by biofuel producing countries is the impact of GHG emissions from LUC on the biofuel GES. Hence (given a selected biofuel pathway), the research focuses on assessing land-use changes induced by the production of feedstock for biofuels. The research explores the effect of key factors influencing this result, including market dynamics in the biofuel supply chain, regional land-use change patterns, feedstock cultivation methods and the domestic policy framework of the biofuel producing country.

The four main objectives on the research are stated below:

- Assess market dynamics of the main products of the biofuel supply chain.
- Assess the effect of government policies on the biofuel export potential.
- Assess the effect of land-use change on the biofuel GES.
- Assess the effect of the EU-RED GES threshold on AR biofuel exports.

This thesis builds on the development of a modeling and simulation framework for the Argentinean case, a major soybean-based biodiesel exporting country. This case study is chosen mainly due to the following reasons:

- The potential of the country as a biodiesel producer and exporter.
- The variety of policy instruments affecting the biodiesel supply chain.
- The agro-exporting structure of the country and its implication for international markets.
- The historical significance of soybean production as a driver of land-use change.

The assessment of the Argentinean soybean-based biodiesel export potential to the EU under the EU-RED GES threshold undergoes several tasks and limitations.

Firstly, **actors' interaction** in the soybean-based biodiesel supply chain should be defined. The biodiesel supply chain entails several actors that involve producers of soybean and value-added products, input suppliers and consumers which interact in their respective markets. Despite many actors linked in the biodiesel supply chain, this thesis focuses on the role of producers of soybean and value-added products. Producers have specific production technologies and supply soybean and value-added products to the domestic and international markets.

Secondly, the effect of international prices of soybean and value-added products on land supply for soybean production should be assessed. **Plausible scenarios** of the evolution of these factors are developed to determine how Argentinean producers respond to international prices and how international market dynamics are affected by the supply of AR producers. While several plausible scenarios can be tested, simulation experiments draw on a single representative scenario of the evolution of international prices and demand for soybean and value-added products.

Thirdly, **government policies** affect the profitability of producers involved in the biofuel supply chain. In the Argentinean case, specific policy instruments regulate the domestic biodiesel market. Additionally, complementary policies regulate the soybean and fuel sectors. Simulation experiments are performed to assess producers' response with respect to changes in government policies. While several policy cases can be tested, simulations focus on the effect of the domestic biodiesel policy instruments and the effect of *ad-valorem* export taxes on the supply of soybean and value-added products.

Finally, GHG emissions from land-use change depend mainly on production patterns in the supply of feedstock. In the Argentinean case, soybean cultivation methods and agricultural land expansion patterns differ among locations from where soybeans are obtained. **Simulation experiments** are performed to assess GHG emissions from land-use change when including different soybean production patterns at the regional level.

1.4. Framework of the methodology

An integrated modeling framework is proposed to assess the biodiesel export potential of Argentina under GHG emission restrictions imposed in the EU-RED. The modeling framework allows assessing the impact of biofuels production with respect to land-use changes and GHG emissions by explicitly modeling the interaction between producers in the biodiesel supply chain and their link to international markets, the supply of land for soybean production and the GES of the biofuel.

The methodological procedure to implement the modeling and simulation framework for the Argentinean case, involves the following tasks (Figure 1-2).

In the first place, an **analysis of the market structure and dynamics** in the national and international market for soybean products is performed. The analysis identifies the main characteristics of the biodiesel supply chain and the links to international markets. Based on this analysis, the structure of the biodiesel supply chain and scenarios of the market evolution for AR soybean products are defined to assess the supply response of AR producers. The impact of soybean production on LUC and the soybean-based biodiesel GHG emission balance are analysed in the Argentinean context. Based on this analysis, the modeling foundations for the modeling framework are defined.

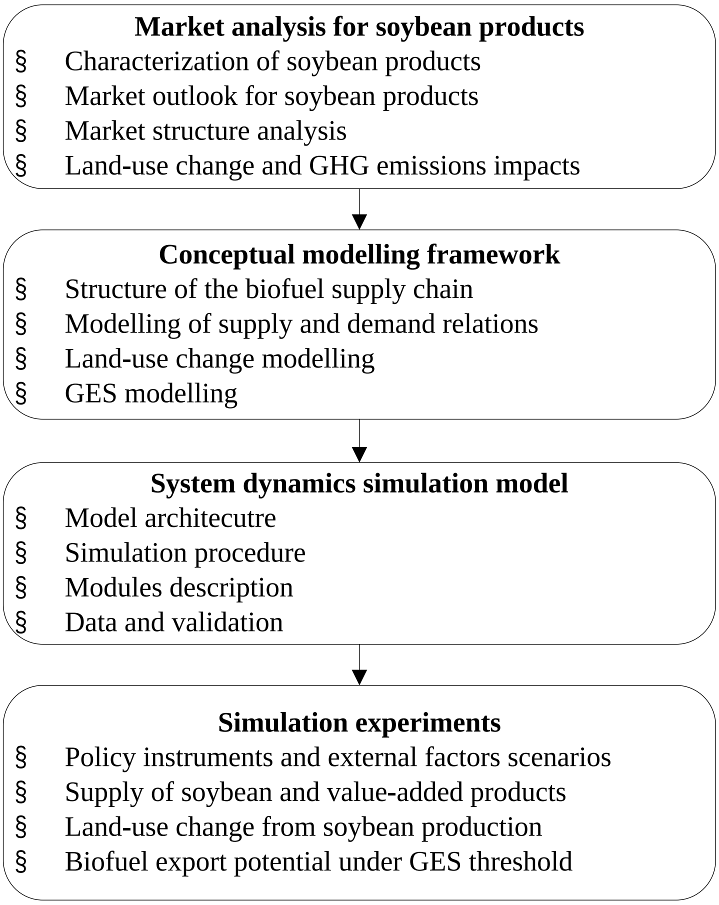

Figure 1-2. Methodological procedure.

In the **conceptual modeling framework** the biodiesel supply chain structure and the interaction among producers, government policies and external factors are formalised. Supply and demand relations are specified for each producer in the biodiesel supply chain. The land structure and the land supply and allocation procedures to determine land-use changes from soybean production are defined. Finally, the modeling foundations for the estimation of the biofuel GES are specified, focusing on direct land-use change and cultivation emissions in soybean production.

The conceptual modeling framework is implemented in a **system dynamics simulation model**. The model architecture and the simulation steps are defined. In each module the simulation procedure and the main feedback interactions are described. The simulation model is built and calibrated upon a significant set of data and validated through conventional validation tests in system dynamics modeling.

Finally several **simulation experiments** are performed. Through different cases the model response to government policies, international market dynamics and production patterns in soybean supply is estimated.

1.4.1. Market analysis and modeling framework

Market structure has a significant effect on how producers behave. In a first step, the market structure and dynamics in the national and international market for soybean products is analysed. Given the main role of Argentina in the international market for soybean products, the linkage between international prices of soybean products and supply by Argentinean firms is assessed. To this end, the main players in the international market and market trends for soybean products are discussed based on Agricultural Outlook projections (FAPRI 2010b; OECD-FAO 2010). Additionally, the market structure of the Argentinean soybean sector and the impact of soybean production on land-use change and GHG emissions are discussed.

Second, based on the previous market analysis, a conceptual modeling framework is developed. The biodiesel supply chain is modeled on classical micro-economic theory of profit maximising firms acting in a competitive environment. The economic model of the supply chain builds on a partial equilibrium (PE) model of the Argentinean soybean sector (Meyers *et al.* 1991). The model however was adapted to include the biodiesel sector and a more detailed representation of land supply for soybean production.

The structure of the **biodiesel supply chain** is defined by specifying demand and supply functions for each producer in the biodiesel supply chain. The agro-exporting structure of the Argentinean soybean processing industry determines the dependence of demand for Argentinean soybean products on structural factors and prices affecting the international market of soybean oil and meal. The specification of demand functions therefore accounts for exogenous demand shifters and the effect of price. In the case of biodiesel, specific demand functions are formulated to explicitly account for demand drivers in the domestic and international markets.

On the supply side, producers' supply functions are built on the profit maximisation problem of competitive firms. Production functions are specified based on the available technology and the production factors used to supply each soybean product. Constant elasticity single input supply functions are defined that account for producers' response to international prices, government policies and production costs. In the biodiesel sector producers are aggregated in two types to account for specific policy instruments and different production costs affecting the biodiesel export potential. Price transmission equations are formulated to account for the effect of government policies on producers' prices.

Land-use change modeling is performed as follows. The land supply model is adapted from the EPA integrated approach (EPA 2010b), with a specific disaggregation of cropland expansion patterns by region. Firstly, land is disaggregated in hierarchical levels. An allocation procedure distributes land among competing agricultural land-uses. Land allocation is based on the classic profit maximising problem of the land owner. A representative land owner allocates managed land based on relative land unit profits (Hertel *et al.* 2008a). Land profits are estimated based on prices, yields and production costs projections. Nested constant elasticity of transformation functions (Powell and Gruen 1968) are defined to model the possibility of transformation among competing land-uses. Heterogeneity in land productivity is accounted for by defining different land supply curves for pasture and cropland, based on the productivity index approach (van Meijl *et al.* 2006).

Agricultural land supply depends on the possibility to expand managed land into unmanaged lands. The share of converted unmanaged lands on land supply for agricultural uses is exogenously specified. Expansion into unmanaged lands is based on a conventional approach, assuming historical land conversion trends for each unmanaged land-use type. However, different patterns are assumed for different locations of soybean production. Finally, land-use changes from soybean production are allocated to biodiesel, taking into account additional demand drivers of soybean production.

The **biofuel GES** is assessed through a life cycle assessment (LCA) model. The LCA model is based on bioenergy life cycle inventories available in the ecoinvent® database (Jungbluth *et al.* 2007). The model constructs on earlier work, by “dynamising” an attributional LCA of soybean-base biodiesel production for export in Argentina (Panichelli *et al.* 2009). The methodology, however, is adapted, based on the European methodology for LCA GHG emissions estimations in biofuel pathways (EC 2009). The LCA model is particularly detailed for the agricultural phase, including different soybean cultivation methods and GHG emissions from LUC.

1.4.2. Scenario-based approach

International demand for soybean products and the linked international price are subject to significant uncertainty that may result from stochastic processes or from the inherent epistemic uncertainty about the market evolution (Walker *et al.* 2003). Stochastic uncertainty arises from conjectural factors that deal with model inputs variability resulting from random events (e.g. climatic conditions variability, prices volatility). Epistemic uncertainty on the other hand, arises from our ignorance or lack of knowledge about the evolution of external factors, which rely mostly on structural factors such as changes in demand drivers or production capacity in importing countries (Swiler *et al.* 2009).

The use of scenarios is one approach to deal with epistemic uncertainty. A scenario is a plausible description of how the environment in which actors interact may develop in the future (Benedetti *et al.* 2009). To be plausible, it should be based on a coherent and internally consistent set of assumptions about key relationships and driving forces. Contrary to stochastic uncertainty, where the functional relationships are well described and a statistical expression of the uncertainty can be formulated, scenario uncertainty implies that there is a range of possible outcomes, but the mechanisms leading to these outcomes are not well understood (Aligica 2005). Moreover, as scenario variables are interconnected, the development of scenarios should prove consistent with respect to the main assumption underling their evolution over time.

In this research a scenario-based approach is used to generate a single representative scenario of the evolution of international markets, specifically market trends with respect to prices and demand for Argentinean soybean products. Disregarding uncertainty steaming from model structures and parameters estimations, it is assumed that the main uncertainty of the system stems from epistemic uncertainty on the evolution of international markets. To assure consistency in the interconnection of prices and demand the scenario is based on agricultural outlook projections. The scenario is built based on the FAPRI 2010 Agricultural outlook (FAPRI 2010b) that provides future trends of the evolution of agricultural markets from 2010-2025. While other market projections are available, this database was chosen because of a better disaggregation of price and demand data than other databases and the availability of a elasticity database (FAPRI 2010a) that provide parameter values to calibrate supply and demand functions. The modeling framework however can use any set of plausible scenarios.

1.4.3. System dynamics simulation

A **simulation approach** is required to account for variable evolution over time and their feedback effect. System dynamics (SD) is therefore proposed as a modeling environment for the implementation of the modeling framework. Appendix 9.2 provides the theoretical foundations for SD simulation.

System dynamics is a simulation technique which aims to understand the dynamic behaviour of social systems, learn about the complexity of such systems and the underlying causes of their behaviour (Forrester 1971). SD reflects actors' decision in a dynamic modeling environment, where the basic concept is the identification of closed-loop feedback structures (Forrester 1961). Feedback structures are represented as *causal loop diagrams* (CLDs) and implemented in the simulation model as *stock and flow diagrams* (SFD) (Sterman 2000).This is a central feature of SD modeling that motivated the choice of the simulation approach.

The simulation model, therefore, builds on the identification of positive and negative feedback loops driving the dynamics of soybean-based biodiesel production and export under GHG emission constraints. The model needs to takes into consideration the main feedback structures and delays driving dynamics in the biofuel supply chain, land-use changes and GHG emissions. Two main feedback structures are addressed, namely: 1) the interaction between international prices and the supply of soybean products to the international market by Argentinean firms and 2) the interaction between biodiesel supply and the GES.

Variables evolution over time needs to be considered to develop prospective estimations of the biofuel export potential. SD simulation is governed by the passage of time and known as ''time-step'' simulation (Coyle 1996). A "time-step" simulation approach was preferred to other static or recursive dynamic approaches. This certainly adds complexity to the model development, but leads to a more consistent representation of the system evolution over time. The simulation model is implemented in Vensim® DSS software with a specific time horizon from 2001 to 2025.

1.5. Original features of the research

The main contribution of this research is the assessment of the effect of **GHG emissions from land-use changes** on the export potential of a biofuel producer. The assessment allows estimating the quantity of biofuel that a country can export by fulfilling the biofuel GES threshold imposed in importing countries. Key variables influencing this result are the location of the feedstock, the market dynamics of the main products of the biofuel supply chain and the government policies regulating these products. The assessment is performed for the case of soybean-based biodiesel production in Argentina. The original features of the research are summarised as follows.

Specificities in the biofuel sector are explicitly modeled. In the case of Argentina, these specificities are accounted in two forms. The first type addressed the allocation of biodiesel production between the domestic and international markets. To this end, the quantity of biodiesel supplied to each market destination is estimated in relation to the main policy instruments regulating the Argentinean biodiesel industry. The second type involves the allocation of biodiesel supply among two typologies of producers, namely, small and medium (*s&m*) and large (*lg*) firms. To this end, the quantity of biodiesel supplied by *s&m* and large biodiesel producers is assessed based on their respective cost structures and conversion efficiencies. This detailed assessment allowed consideration of the specific regulations affecting the biodiesel export potential in the Argentinean context.

Dynamics in the international markets affecting the biofuel supply chain are explicitly modeled. In the case of soybean, additional drivers of soybean demand largely determine land supply for soybean production that in turn affects land-use changes induce by soybean production. A critical analysis of the market structure and market projections for soybean, oil, meal and biodiesel is performed. A single plausible scenario is then proposed to account for the price and demand evolution of these products. Producer models are developed to specify the supply-price relation and dynamic simulation experiments are performed to estimate the amount of soybean products supplied to the international market given this scenario. Assessing the effect of international market dynamics allowed consideration of the complex environment in which the Argentinean biodiesel industry is developed.

Finally, compared with the traditional approach based on average national values, the GES of the biofuel is estimated for different regions. Biofuels GES can largely vary depending on the **location of the feedstock**. In order to assess the effect of these regional differences, the modeling approach accounts for different soybean production patterns specific for each region. Considering these regional differences allowed analysis of the biodiesel export potential at the sub-national level and demonstrates the importance of feedstock production patterns on assessing dLUC GHG emissions. Regions that comply (or not) with the GES threshold specified in the EU-RED are identified.

1.6. Outline of the thesis

After this introduction, Chapter 2 discusses key modeling choices to address GHG emissions from LUC induced by the production of biofuels. Based on a review of selected models, several aspects for consideration when designing models for this purpose are analysed.

Chapter 3 analyses the market dynamics in the international and domestic soybean sector. The aim of this chapter is the definition of the contextual factors affecting the biodiesel export potential and its implications on land-use change and GHG emissions in the Argentinean case.

Based on Chapter 3, Chapter 4 proposes a conceptual modeling framework to account for the main interactions between producers in the biodiesel supply chain, the modeling foundations of land supply for soybean production and the estimation of the biodiesel GES.

Chapter 5, implements the modeling framework in a system dynamics simulation model. This chapter is focused on the identification of the main feedback structures, the description of the model architecture, the simulation procedure and data and validation of the simulation model.

Chapter 6 presents the simulation experiments to assess the biodiesel export potential under GHG emissions constraints. The chapter focuses on assessing biodiesel market dynamics, the supply of land for soybean production and its implications for LUC and GHG emissions.

Finally, Chapter 7 presents the main conclusions of the research, stating the main limitations and directions for further research.

2. Key modeling choices to assess biofuels production impact on LUC and GHG emissions

2.1. Overview of modeling approaches

In recent years, the number of reviews dealing with biofuels, LUC and GHG emissions has grown sharply. While the literature on these issues is vast, a critical assessment of key modeling issues to address the linkage among these three issues has not been performed. Therefore this chapter critically reviews key modeling choices to assess the impact of biofuel production on land-use changes and GHG emissions. The review builds on selected models that have been already used for this purpose.

Several authors provide comprehensive reviews of land-use modeling approaches (Briassoulis 2000; Lesschen *et al.* 2005; Stratus Consulting Inc 2005). Moreover, economic approaches to assess the impact of agricultural policies have also been extensively reviewed (Hallam 1987; van Tongeren *et al.* 2002; Gardebroek and Oude Lansink 2008; Tschirhart 2009). Consistent reviews of agricultural sector models applied to the assessment of land-use changes induced by energy crops demand have also been performed (van Tongeren *et al.* 2002; Gnansounou and Panichelli 2008; Witzke *et al.* 2008; CBES 2009; Demirbas 2009). Parker *et al.* (2002) and Mathews and Goldsztein (2009) give extensive reviews of agent-based models applied to land-use change modeling, but little work has been done to analyse the impact of biofuels production (Happe *et al.* 2004; Bao Le *et al.* 2008). GHG emissions balances of biofuel pathways are treated in the literature, stating the main methodological challenges and how LUC can be integrated into LCA (Baitz *et al.* 2000; Brentrup *et al.* 2004; Canals *et al.* 2007; Gnansounou *et al.* 2009). Finally, Larson (2006), Cherubini (2009) and Malça and Freire (2010) provide consistent reviews of GHG emission balances of biofuels.

Table 2-1 gives a general overview of the selected models. The models in Table 2-1 are used to explore how key modeling issues are being represented in current modeling approaches. The model class and focus refers to the specific models that have been reviewed.

Equilibrium models apply theory of general (or partial) equilibrium explaining the relation between supply, demand and prices through the satisfaction of a set of simultaneous equilibrium equations (Hertel and Tsigas 1997). While general equilibrium models represent the whole economy and the interactions between different sectors, partial equilibrium models gain in a detailed description of a specific sector (or sectors) and finds equilibrium prices for a specific market (or a limited set of markets). Selected general equilibrium models include the Global Trade Analysis Project (GTAP)[2], the Agricultural Economics Research Institute Trade Analysis Project (LEITAP)[3], the Emissions Predictions and Policy Analysis model (EPPA)[4], the Dynamic Applied Regional Trade (DART)[5] model, and the Future Agricultural Resources

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[2] https://www.gtap.agecon.purdue.edu/models/

[3] http://www.lei.wur.nl/UK/newsagenda/Dossiers/Biobased_economy.htm

[4] http://globalchange.mit.edu/igsm/eppa.html

[5] http://bsi.fsu.edu

Model (FARM) (Darwin 1998). Most partial equilibrium models dealing with biofuels and land-use change are agricultural models, namely FAPRI[6], FASOM (Adams *et al.* 1996) (and their global and European versions, GLOBIOM[7] and EUFASOM (Schneider *et al.* 2008) respectively), IMPACT[8], AgLink (Conforti and Londero 2001), CAPRI[9], ESIM (Banse *et al.* 2005), and energy sector models, such as POLE[10] and PRIMES (NTUA 2008) among others.

Table 2-1. Overview of selected models.

Models	**Type**	**Class**	**Focus**
GTAP, LEITAP, EPPA, DART, FARM	General equilibrium	Static or recursive dynamic, non-spatial, economic, aggregated actors, policy oriented	Global, supply-demand-trade, policy analysis
AgLink, ESIM, FAPRI, CAPRI, IMPACT, PEM, POLE, PRIMES	Partial equilibrium	Recursive dynamic, non-spatial, economic, aggregated actors, policy oriented	Global, supply-demand-trade, policy analysis for the agricultural and energy sectors
GLOBIOM, EUFASOM, FASOM, LUCEA, P&G, POLYSIS	Optimisation	Recursive dynamic, non-spatial, linear programming, aggregated actors, policy oriented	Profit/welfare maximisation, policy analysis
CLUE, LANDShift, KLUM	Spatial	Spatial, cellular automata, remote sensing, empirical-statistical, disaggregated actors	Land allocation, spatial patterns
EPIC, IMAGE	Biophysical	Spatial, Static	Calibration of bio-physical parameters, estimation of bio-physical variables
C&S, B&S, G4M	Agent-based	Spatial, dynamic, local, disaggregated actors	Individual heterogeneous actors decision
S&G, GLUE, TIMER, BDM, BSM	System dynamics	Non-spatial, dynamic, aggregated actors, policy oriented	Time delays, feedbacks, policy analysis, biofuels diffusion
GREET, Ecoinvent, GHGenius	Life Cycle Analysis	Static, non-spatial, feedstock specific, national-regional	GHG emissions balance

Optimisation models aim to optimally allocate resources by maximising or minimising an objective function, generally an economic objective function of profit, utility or welfare. The Land Use Change Energy and Agriculture Model (LUCEA[47]), the Regional Environment and Agriculture Programming Model (REAP) and the Policy Analysis System (POLYSIS[11]) models are currently being applied to estimate the impact of bioenergy production on land-use change.

Spatially explicit models focus on the spatial allocation of land resources. Cellular automata (Batty *et al.* 1999), neural networks (Pijanowski *et al.* 2002), and remote sensing (Cardille and Foley 2003; de Barros Ferraz *et al.* 2005) are examples of land allocation techniques.

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[6] http://www.fapri.iastate.edu/models/
[7] http://www.iiasa.ac.at/Research/FOR/globiom.html
[8] http://www.ifpri.org/themes/impact/impactresearch.asp
[9] http://www.ec4macs.eu/home/capri-news.html
[10] http://www.enerdata.fr/enerdatauk/tools/Model_POLES.html
[11] http://www.agpolicy.org/polysys.htm

Relevant models dealing with biofuels account for the Land-use Change and its Effects (CLUE), KLUM (Ronneberger 2006) and LandShift[12] models.

Biophysical models aims to describe ecological and environmental processes. They assess for example, the impact of climate change on crop yields and land productivity. Relevant examples applied to biofuels account for the Environmental Policy Integrated Climate (EPIC) and the Integrated Model to Assess the Global Environment (IMAGE) models.

Agent-based models (ABM) focus on simulation of individual actors' decisions. They account for local/regional actors' behaviour, preferences and heterogeneity to simulate the emerging behaviour of the system. However, ABM applications to estimate impacts of biofuels production on land-use change are still scarce.

System dynamics models (SD) assess the time dependent behaviour of complex social systems. They focus on the identification of feedback structures to generate endogenous explanations of the system behaviour. Several system dynamics models are being used to simulate biofuel diffusion processes (Bantz and Deaton 2006; Bush *et al.* 2008; Malczynski *et al.* 2009).

Life cycle assessment models (LCA) evaluates the environmental impact of a product through the quantification of input and output flows. While attributional LCA (ALCA) assesses the average environmental properties of a particular product, consequential LCA (CLCA) assesses the consequence of a decision. At present CLCA is the adopted methodology to assess land-use impacts induced by biofuel production (Kløverpris *et al.* 2008a; Brander *et al.* 2009; Winrock 2009). GREET[13], Ecoinvent[14] and GHGenius[15] are the main models being applied to develop attributional and consequential LCAs.

Key modeling issues to address biofuel production impact on GHG emissions from LUC include the following aspects:

- **Objective and scope of the model:** The objective and scope of the modeling approach states clearly the intended purpose of the model and the dimension of the problem to which the modeling approach aims to address.
- **Level of representation of policies:** The degree of detail on the representation of biofuel policies includes the modeling of policy objectives and instruments, which may include also the accompanying policies regulating the biofuel supply chain.
- **Actors' representation and aggregation issues:** Actors' representation includes the definition of main actors to be considered and the level of aggregation.
- **Scale and system boundaries:** Choice of spatial and temporal scale and system boundaries of the model determine which parameters and processes are included.
- **Spatial and time dynamics:** Spatial patterns and the system evolution over time include the spatial heterogeneity of land, the co-relation of land-use conversion pathways, the time horizon of the policy and delays in actors' decisions.

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[12] http://www.usf.uni-kassel.de/

[13] http://www.transportation.anl.gov/software/GREET/

[14] http://www.ecoinvent.ch/

[15] http://www.ghgenius.ca/

The next sections identify some limitations and improvements in current models to evaluate the impact of biofuel production on LUC and GHG emissions.

2.2. Scope and objective of the model

2.2.1. Techno-economic impacts of biofuels production

Economic impacts of biofuels production are typically covered by general/partial equilibrium, optimisation and system dynamics models. Modeling techniques, however, vary between these approaches making them suitable for different purposes. In the context of biofuels, equilibrium models have mainly applied to assess micro-economic consequences of biofuels production. They assessed the impact of biofuel mandates on feedstock international prices given an exogenous shock in feedstock demand. SD models on the other hand addressed mainly the diffusion process of biofuels. They abstract from equilibrium conditions and study the necessary conditions needed to achieve the required biofuel mandate level. Optimisation models assessed social welfare implications of biofuel production.

Computable general equilibrium models are top-down models that link general equilibrium theory with realistic data of a given economy in order to find the supply, demand and price levels that support equilibrium across interconnected markets of an opened economy (Wing, 2004). Goods production is typically represented by nested constant elasticity of substitution (CES) functions including primary production factors and intermediate inputs. Through the introduction of market distortions they study the impact of a change in price on production, consumption and trade patterns. These models have been mainly used to analyse climate change and agricultural reform policies. The GTAP model, for instance was designed to analyse trade interaction in the global economy (Hertel and Tsigas 1997).

These models however were developed for other purposes. Consequently, significant adaptations have been required to include the biofuel sector. In the case of the reviewed general equilibrium models, the introduction of biofuels is mainly performed by linking the energy and agricultural sectors. The GTAP-E model (Burniaux and Truong 2002), for example, is an extended version of the GTAP model that has an explicit representation of the energy sector. GTAP-E has the same structure as GTAP, but its production structure includes a more detailed description of substitution possibilities among different sources of energy. Taheripour *et al.* (2008) have developed the GTAP-BIO database that explicitly includes biofuels as a sector. Biodiesel for instance, is linked to the vegetable oil and fats sector. Birur *et al.* (2008) further disaggregated the biofuel sector in the GTAP-E model. In the EPPA model, on the other hand, biomass energy has been introduced as a perfect substitute of fossil fuels in the refined oil sector (Reilly and Paltsev 2008). While this is an acceptable alternative to address current public debate on the global impact of biofuels production, a more reasonable approach would consist in developing models specifically designed to account for specificities in the biofuel sector.

To this end, system dynamic models focus on representing specific biofuel supply chains and the real diffusion process of biofuel technologies. In a study by Bantz and Deaton (2006), for instance, the SD model aims to understand the evolution of the biodiesel industry based on four modules representing the diesel, biodiesel, glycerol and biomass oil sectors. The model estimates the feedstock availability and the biodiesel/diesel and glycerol prices accounting for governmental regulations and incentives driving supply and demand of each product in the biodiesel supply chain. Malczynski *et al.* (2009), on the other hand, developed the Biofuel Deployment Model (BDM), a dynamic supply chain model applied to the cellulosic ethanol industry. The model aims to understand how certain variables affect the cost and volume of ethanol production. Additionally, Bush *et al.* (2008) also focus on the cellulosic ethanol industry. They developed the Biomass Scenario Model (BSM) to simulate the evolution of the cellulosic ethanol supply chain industry in the US. The model accounts for competition in the oil market, vehicle demand for biofuels and government regulations over time. Specific government policies and external economic factors are evaluated to assess their impact on investment decisions in the cellulosic ethanol industry. However, the reviewed SD models rely on simple structures that mimic the overall behaviour of the system. While this can be an advantage to avoid models integration it can be a simplistic approach to quantitative analysed complex interactions such as the linkage among biofuels, LUC and GHG emissions.

Optimisation models are useful for efficiency analysis purposes. In these models the objective function to be maximised generally relies on a welfare measure. The REAP model, for example, is a mathematical programming model of US agriculture that maximises the net social benefit (Johansson *et al.* 2007). This welfare approach is useful to assess the economic externalities generated by biofuel production. Optimisation models can also be applied to assess environmental externalities, for example, in a study by Panichelli and Gnansounou (2008) a constrained non-linear optimisation model is used to perform efficiency analysis of biofuel production strategies with respect to the carbon pay-back time[16]. The model calculates GHG emissions from direct and indirect LUC based on assumptions about feedstock production and potential displacements of other activities. Similarly to equilibrium models, the main limitation here is the assumed optimality conditions. Complex dynamic systems normally do not behave in an optimal way. This is due for example, to the presence of non-linear behaviour, incomplete information and the bounded rationality of economic agents.

2.2.2. Land-use change impacts of biofuel production

Impacts on land-use change are typically addressed through spatially explicit models. Spatial models allocate land based on historical land-use transitions or based on agro-ecological and infrastructure factors. Land allocation is mainly estimated through regression models of location variables (Verburg *et al.* 1999; Aguiar *et al.* 2007) or through Markov models of transition probabilities. Transition probabilities can be estimated mainly through satellite images classifications (Leeuwen *et al.* 2006; Vega *et al.* 2009) or statistical analysis (de Koning *et al.* 1998; Braimoh and Onishi 2007). The CLUE (Land-use Change and its Effects) model, for instance, is a geo-referenced model for the analysis of LUC (Veldkamp and Fresco 1996; Veldkamp and Lambin 2001). CLUE mainly uses regression analysis to estimate land-use transitions based on a set of variables that are assumed to guide land-manager decisions on land allocation. On the other hand, LandShift[17], for example, is a spatially explicit land-use change model based on the integration of socio-economic and biophysical components of land-use systems. LandShift was used to estimate the impact of biofuels production on land allocation at a country level (Lapola *et al.* 2010; Schaldach *et al.* 2011).

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[16] Number of years that a biofuel should be used to offset emissions from land-use change on feedstock cultivation.

[17] http://www.usf.uni-kassel.de/cesr/

The main limitation of spatially explicit models is that as they focus on location patterns, their representation of economic drivers of LUC is limited. This motivated the link of spatial explicit models with economic approaches. KLUM (Ronneberger 2006), for instance, is a land-use model that was linked to a modified version of the GTAP model to account for macro-economic variables driving land allocation decisions. The models are linked by replacing the land allocation mechanism of GTAP-EFL with KLUM. Land allocation depends on the profit maximisation decision of the land-owner in response to GTAP equilibrium prices and biophysical characteristics of land that define the crop yield. Crop yields are exogenously introduced by linking the KLUM model to the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model. Moreover, the CLUE[18] model has also been linked to the GTAP model to account for macro-economic drivers of LUC (Hellmann and Verburg 2010, 2011).

In economic models, the traditional approach to allocate land among competing land-uses is based on the constant elasticity of transformation (CET) function (Powell and Gruen 1968). Darwin *et al.* (1996) proposed an approach relying on CET functions to represent substitution among crop sectors. Most land-use change models, such as FARM (Darwin 1998) and KLUM (Ronneberger *et al.* 2005) rely on this approach. The CET function postulates that land owners maximise total land profits by allocating their land among different uses, subjected to the availability of land and the possibility of transformation among them. The land supply elasticity varies as a function of the constant elasticity of transformation and the relative importance of a given activity, measured as land value (Hertel *et al.* 2008b). The GTAP-PEM model also follows this approach, based on the estimation of elasticities of substitution for OECD countries (OECD 2003). Additionally, Golub *et al.* (2008) also implemented this framework but they distinguish land substitution between different zones within each country using data on the agro-ecological characteristics of land to more precisely represent the potential reallocation of land. A problem with the CET function however is that as it allocates land based on land value, it is difficult to track land-use changes in physical units (Nassar *et al.* 2011). Gurgel *et al.* (2007) addressed this problem through a modified version of the CET function assuming that 1 hectare of land of one type is converted to 1 hectare of another type, and through conversion it takes on the productivity level of the new land-use.

From an economic perspective, the problem with the representation of managed land supply is that provided that native lands are generally not under economic use, it becomes difficult to estimate its economic value. Consequently, it becomes difficult to estimate the possibility of land transformation based on the conventional CET function. Probably for this reason most economic models have assumed land as a fixed input and allocate land only among economic uses (Hertel *et al.* 2008a). However, for the purpose of assessing land-use change impacts of biofuels production, this approach is not sufficient. Some improvements have been introduced in some economic models to assess the impact of the demand for agricultural commodities for example, the LINKAGE model incorporates some possible land expansion based on the variation of an aggregated land price (van der Mensbrugghe 2005). A study by van Meijl *et al.* (2006) moreover, suggested the use of biophysical data to calibrate land supply functions based on marginal productivity information. The advantage of this approach is that asymptotic limits to land expansion and decreasing returns to scale can be modeled explicitly (Tabeau *et al.* 2009).

The second issue to be considered in representing managed land expansion is the definition of which unmanaged land-uses are displaced by the expansion of the agricultural frontier (Nassar *et al.* 2011). This is especially important because the share of each unmanaged land-use on

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[18] http://www.cluemodel.nl/

cropland expansion largely determines the impact of biodiesel production on land-use change and GHG emissions (Edwards *et al.* 2010a). The conventional approach to estimate these shares is to assume that agricultural land expansion will follow the same patterns as historical land-use change trends. Studies by Al-Riffai *et al.* (2010) and Searchinger *et al.* (2008) respectively, applied this approach by assuming historical shares of native ecosystems to allocate agricultural production displaced by biofuels production. Alternatively, land supply functions can be specified by estimating land transformation elasticities for managed lands expansion into unmanaged lands. The transformation elasticity can be estimated for instance, using land-use transition probabilities (Ahmed *et al.* 2008). A conventional approach for this estimation is to use time series satellite images (López *et al.* 2001; Kamusoko *et al.* 2009). However this approach would require detailed geo-referenced data and additional computational efforts.

The impact of biofuels production on land-use change has also been studied through system dynamics simulation models. However, their treatment is significantly simplified. Yamamoto (1999; 2000; 2001), for instance, have applied SD to develop a global land-use and energy model (GLUE). The model evaluates the biomass resources potential for bioenergy production including land-use competition among various uses of biomass resources. Additionally, several SD models are being used to simulate the biofuel supply chain in the US including land in the feedstock-production phase and GHG emissions from indirect land-use changes (Monson 2008; Stamboulis and Papachristos 2008; Malczynski *et al.* 2009; West *et al.* 2009). A study by Sheehan (2009b), has focused on estimating global land-use changes induced by cellulosic bioethanol production in the US. The model however does not account for economics in the biofuel supply chain and focuses mainly on estimating the GHG emission balance of US ethanol including direct and indirect land-use change at the global level. At the regional level, the impact of bioenergy production on GHG emissions has been addressed in work by Szarka *et al.* (2008). Their model allows simulating the quantitative effects of regional biomass alternatives for energetic purpose in the Austrian-Hungarian cross-border area. Agricultural policies impact on land-use and food security at the regional level are also addressed in research undertaken by Saeed *et al.* (2000).

2.2.3. GHG emission impact of biofuel production

The most appropriate and widely-applied methodology to determine the GHG balance of a biofuel pathway is the Life Cycle Assessment (LCA). This tool evaluates the environmental impact of a product through the quantification of input and output flows. The conventional approach is to use the so-called attributional LCA (ALCA). However this is a static approach and in consequence dynamic processes are not considered. Static modeling does not account for price variations, changes in demand or technological improvements. Consequently, several authors have applied the so called “Consequential LCA” (CLCA) to assess land-use impacts induced by biofuel policies (Kløverpris *et al.* 2008a; Brander *et al.* 2009; Winrock 2009). The CLCA evaluates the changes produced in a system as a consequence of a decision.

Three main models and inventory databases are being applied to develop attributional and consequential LCAs, namely, GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation)[19], ecoinvent® and GHGenius[20]. The GREET model examines a large set of U.S. transportation fuels, including biofuels and vehicle systems. Ecoinvent® is mainly

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[19] http://www.transportation.anl.gov/software/GREET/

[20] http://www.ghgenius.ca/

a database of life cycle inventories (Frischknecht *et al.* 2005) mostly used in the EU. The database is composed of life cycle inventories of productions and processes and a database of life cycle impact assessment methods. It has been widely applied to perform LCA of biofuel pathways (Jungbluth *et al.* 2007). GHGenius is an LCA model for the transportation sector, maintained by Natural Resources Canada. It is a spreadsheet model that calculates the well-to-wheel GHG emissions of transportation fuels and technologies.

To date, these LCA tools have considered direct LUC and associated GHG emissions but required the integration with other modeling approaches or the expansion of existing models, for instance, in a study by Searchinger *et al.* (2008), the FAPRI international model[21] is used to allocate displaced corn production for other purposes and soybean displaced from rotation in the same land. Converted land is assigned based on the proportion of lands that have been transformed into cropland in the past. This data is used as input for the GREET model to calculate the GHG balance of US corn-based bioethanol. On the other hand, the US EPA (EPA 2010b) developed an integrated approach linking several models. The impact of US biofuel mandates on global land-use demand is estimated by linking the GTAP-FAPRI models. Land-use changes at the country level are estimated through the FASOM optimisation model. Finally, GHG emissions from biofuels production and use are estimated based on the Winrock and GREET models. These integrated approaches have been mainly used to assess indirect LUC GHG emissions from biofuels productions. However, they do not account for the effect of GHG emissions restriction of biofuels production and exports.

Endogenous estimation of LUC GHG emissions have also been improved in economic models (Lee *et al.* 2005). While this approach is pertinent for macro-analysis of biofuel policies, their application to smaller scales of analysis will required a more detailed representation of the system components.

2.3. Level of representation of biofuel policies

2.3.1. Inclusion of policy objectives

Biofuel policy objectives define the main goals to be achieved by the implementation of the policy. Different countries have stated different reasons for supporting biofuels. The underlying motivation for biofuel policies rely among others on the volatility of crude oil price, the increased geopolitical conflicts in crude oil supply, the increased awareness of the impact of climate change and the vulnerability of rural sectors in achieving economic viability. These motivations have been the milestone for the proposition of biofuel policies as a way to tackle these issues. Policy objectives for biofuels production and use vary between countries as a result of their specific contexts, including level of energy security and independence, commitment to reduce GHG emissions and rural economic conditions. Among policy objectives, most biofuel policies are developed for three purposes: energy security and independence, climate change mitigation and rural economic development

Most of the models reviewed omit the link of the modeling approach to the objectives of the biofuel policies. In the equilibrium model, modeling exercises were more concerned about the impact of biofuels production on LUC GHG emissions. Several efforts have been made to

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[21] http://www.fapri.iastate.edu/models/

adapt the GTAP-E model (Burniaux and Truong 2002) for this purpose. Examples include the assessment of the impact of international biofuel mandates (Hertel *et al.* 2008b), LUC and GHG emissions (Alla *et al.* 2008), and the indirect LUC impact of US biofuel policies (Keeney and Hertel 2008). These adaptations have been useful to address two main unintended consequences of biofuel policies, namely their impact on world food prices and the GHG emissions from LUC. However, an explicit link to the policy objectives is still missing.

Only a few policy oriented studies exist about the impact of biofuels on LUC, accounting mainly for the impact of US and EU policies (Alla *et al.* 2008; Banse *et al.* 2008a; Keeney and Hertel 2008; Tabeau *et al.* 2009; EPA 2010b; Hellmann and Verburg 2010; Britz and Hertel 2011; Havlík *et al.* 2011; Hertel *et al.* 2008b). The FAPRI model was used to analyse the impact of US policies on global markets, therefore, it focuses on modeling the US economy (Tokgoz *et al.* 2007). Moreover, it is included into an integrated modeling framework used by the US Government (EPA 2010b). As developing countries are less concerned about climate change mitigation, the availability of models to assess their biofuel policy objectives is rare.

While current models can be used to address specific policy issues, this link is often omitted. In several models policies are not linked to the underlying analysis of their impact on land-use change. The EPPA model, for example, was used to estimate the impact of the demand for second generation biofuels on land conversion (Gurgel *et al.* 2007; Reilly and Paltsev 2008). A more policyoriented goal would be to assess the impact of government support to second generation biofuels and their consequence on land conversion. Even if they are more policy oriented, other models' representation of biofuel policies is limited. For example, GLOBIOM is a spatial partial equilibrium model of the forest and agricultural sectors used to analyse the interaction between biofuels production and deforestation (Havlík *et al.* 2009). In this case, biofuel policies are indirectly accounted for by defining different scenarios of biofuels production levels by 2030.

On the other hand, the policy perspective has been addressed in other studies by including the effect of different policy instruments and land expansion constraints on land-use change induced by biofuels production. Johansson *et al.* (2007) used the LUCEA (Land Use Change Energy and Agriculture Model) model to assess the effect of carbon taxes on land-use competition for food and bioenergy in the US. Including policy issues in such models can lead to significantly different results, as land allocation patterns can change if policy constraints are included. In a study by Havlik *et al.* (2011), land expansion constraints are included to assess the GES of different biofuel production options. Policy recommendations are also given with respect to the effect of carbon taxes on land-use changes. Agent-based and system dynamic models have also fail to incorporate the policy dimension. In the SD GLUE model (Yamamoto *et al.* 1999) the biomass resources potential for bioenergy production is evaluated, while policy constraints for land expansion have not been considered.

2.3.2. Inclusion of policy instruments

A key feature of biofuel policies is the combination of instruments supporting the supply and demand side of the biofuel sector. Moreover, due to the combined characteristics of biofuels as a substitute to fossil fuel, an environmental good and an agricultural-based product, biofuel policies are generally interlinked with energy, environmental and agricultural policies.

Concerning the representation of biofuel policy instruments, most studies have focused on assessing the impact of biofuel mandates as a driver of land supply for biofuels production. Some models are being applied to estimate the impact of EU and US biofuels mandates on global land-use demand. For instance, POLYSIS is a linear programming model of the US agricultural sector used to analyse land-use change and emissions implications for meeting the US RFS biodiesel and ethanol production targets. The LEITAP model was developed to analyse the impact of EU biofuel mandates on land-use change, agricultural production and food markets (Banse *et al.* 2007; 2008a; 2008b; 2011). The US EPA (EPA 2010b) assessed the impact of US biofuel mandates.

The common procedure to analyse mandate impact on land-use changes is based on model-run comparisons between a baseline without biofuels and an alternative scenario with biofuels. The baseline projection is shocked with the required feedstock quantity (or land quantity) to produce the biofuel target demand. A higher demand for crop-based biofuels increases the crop price. Farmers consequently allocate more land to biofuel crops to equilibrate the supply-demand imbalance, inducing direct land-use changes. This, in turn, will reduce land for other crops and land-uses, increasing prices for the displaced activities.

The main problem with this approach is that in reality the mandate achievement depends among other factors on the policy framework regulating the biofuel supply chain. Subsides, taxes and supply constraints, for instance, can limit the ability of biodiesel producers to supply the required biodiesel quantity to achieve mandate levels (Koplow 2009). Some economic analyses have been performed to assess for instance, the effect of tax credits for biofuels production (Gecan and Johansson 2010) and the subsidies for biofuels production in selected OECD countries (Kutas *et al.* 2007). In equilibrium models, however, little work has been done to assess how different combinations of policy instruments affect LUC induced by biofuels production. The impact of biomass subsidies and conventional electricity taxes in biomass and agricultural commodities was assessed using a national partial equilibrium model. The model was used to determine the impact of these policies on GHG emissions, land allocation and food and electricity prices in Poland (Ignaciuk *et al.* 2006). This type of assessment seems to be linked to regional or national scale models. More detailed data is needed to account for the specificities of the country and biofuel production pathway under study.

The effect of policy instruments on the biofuel supply side has been more extensively treated in SD models. Stamboulis and Papachristos (2008) for instance, developed a simple SD diffusion model to test policy scenarios focusing on the diffusion process of biofuels as a fossil fuel alternative. Moreover, the Biomass Scenario Model (BSM) simulated the evolution of the cellulosic ethanol supply chain industry based on the build-up timing of the infrastructure associated with each system (Bush *et al.* 2008). Specific government policies and external economic factors are evaluated as to their impact on the relative attractiveness of investing in new biofuel technology. Franco *et al.* (2009) focused on simulating the impact of subsides on the development of the Colombian biofuel industry, accounting for a variety of feedstocks and subsidy types. The main limitation of current SD models however, is that their application was limited to the biofuel diffusion process. Even though they account for the effect of different policy instruments on biofuels production levels, their link to LUC and GHG emissions is hardly reflected.

Additionally, other policy instruments may also support or constrain the development of the biofuel industry. Accounting for these accompanying policies may significantly change biofuel production and consumption patterns. This may be the case, for instance, of the EU-

RED GES threshold. None of the models reviewed account for GHG emission constraints in biofuels trade in the international market.

2.4. Actors representation and aggregation issues

2.4.1. Modeling actors' heterogeneity

Most models have an aggregated representation of actors independently of the model scale. This is a problem if the model needs to account for actors' heterogeneity, for example, to evaluate government support to the infant industry or small agricultural producers. Indeed, equilibrium models are typically aggregated models. General equilibrium models represent the whole economy through aggregated economic actors at the national level. The GTAP model, for example, represents the global economy as a multi-region economy. Each regional economy is represented by a representative household that maximises utility and a set of producers of specific goods and services that maximise profit. Each good is assumed to be produced by a single representative firm in each region. While this aggregation level is necessary to handle global models, actors' homogeneity makes models less suitable to account for key country- and context- specific differences. The Brazilian Biodiesel Program, for instance, explicitly supports small agricultural producers (Ministry of Agriculture 2006). The Argentinean biodiesel policy (SyCDNA 2006) explicitly supports small and medium biodiesel producers. Accounting for these policy constraints may significantly influence biofuel production patterns such as the location of feedstock production.

Actors´ heterogeneity is better represented in agent based models. As ABMs focus on simulation of actors' decisions, they overcome some limitations of equilibrium models mainly by including different actors' types and individual decision making processes, for example, in a study by Rossetti *et al.* (2009) the market diffusion of second generation biofuels is based on forecasting investor attractiveness for second generation biofuels technologies. Products are differentiated based on multiple attributes such as price, quality, or environmental performance. Consumers are treated as independent entities with heterogeneous preferences and behaviour capable of both learning and behavioural change. On the other hand, the Stanford-Carnegie Biofuels Project uses agent-based modeling to assess the effects of sugarcane-based ethanol production on land-use distribution in northern Brazil. The model simulate farmer response to increased demand for sugar cane and the displacement effects on competing land cover classes (Fernandez 2008). The level of detail required to account for actors' heterogeneity however, makes these models more suitable for regional or local applications.

Actors' expectations and bounded rationality are typically well represented in SD models. System dynamics allows modeling of the actors' decision processes in a more realistic way by accounting for delays and incomplete information (Smith and van Ackere 2002). Current applications to biofuel diffusion processes however, have relied on relatively simple models with an aggregated representation of actors. In Stamboulis and Papachristos (2008), for instance, the simple SD diffusion model is divided in 3 sectors: biomass production, biofuel production and biofuel use. Biomass production is centred on the provision of land. Biofuels production is represented by the investment on production capacity. Biofuel use is based on the availability of retailing sites and the consumers' demand. Each process is represented by an aggregated actor (i.e. the farmer, the biofuel producer, the consumer) that determines the dynamics of the transition to biofuels.

2.4.2. Aggregation of sectors and regions

Most global models also aggregate regions and economic sectors. In the case of general equilibrium models, as they focus on the whole economy, their representation of sectors and regions is highly aggregated. In the EPPA model, for example, due to its focus on climate change policies, regions were aggregated in Annex B and Non-Annex B countries of the Kyoto Protocol and sectors were aggregated as energy, non-energy and advanced energy technologies. The current disaggregation of countries and sectors constrains the model's ability to assess land-use changes in specific countries. On the other hand, the GTAP model is a multi-regional model of 16 regions and 21 sectors. This GTAP 6 database accounts for 87 countries/regions and 57 products/sectors. However, the level of sectors aggregation do not allow to model for example, decisions on biofuel feedstock type, especially for the case of biodiesel where oilseeds and oleaginous fruits are treated as a single aggregate as well as vegetable oils.

This type of aggregation that is suitable for assessing global impacts is less suitable to assess specific biofuel pathways. This occurs because it is impossible to track a specific biofuel supply chain. Current general equilibrium models only account for sugarcane-beet ethanol, coarse-grains ethanol (GTAP, LEITAP), wheat ethanol (LEITAP), and average lingo-cellulosic ethanol (EPPA) production pathways. Feedstock selection by a biofuel producer within the country is not possible. Moreover, regional specificities are not accounted for, constraining the ability of global models to assess specific biofuel supply chains. On the other hand, biofuels eligibility for the EU-RED, for example, specifies GES for specific biofuel production pathways. Therefore complementary models may be developed focusing on specific biofuel supply chains.

With respect to land-use change, aggregation also results in some limitations. Land aggregation is not suitable to study the eligibility of regions as feedstock production areas. In the EU-RED, for example, command and control instruments are used to regulate feedstock location. This criterion implies for example, that feedstock cannot be cultivated in forest land with more than 30% canopy cover. Accounting for this criterion will imply disaggregating forest land in different types. Some work is being done to overcome this limitation by adapting existing land-use databases (Carré *et al.* 2010; Hiederer *et al.* 2010). However, their integration into models and policy analysis is still missing.

Finally, in some cases the biofuel policy aims to promote cultivation in certain land-use types. In the EU-RED for example, a credit is given for energy crops cultivation in set aside land. Consequently the land-aggregation level should specify a set-aside land-use category. These constraints and incentives can significantly change land-use allocation patterns. Unfortunately, this is not considered in current models as land-use aggregation does not allow performance of such an analysis.

2.5. Scale issues and system boundaries

2.5.1. Regional, national and global models

Scale choices are sometimes limited by the underlying structure of the models, which limit their application to assess certain issues. Equilibrium models have been mainly applied to assess the worldwide implications of biofuel production. In the context of this assessment, the typical scale of these models is the whole world. The AGLINK-COSIMO model, for example, is a dynamic multi-region model of the world agricultural sector. The model is used to develop medium-term scenarios of supply, demand and prices of agricultural product and to analyse the impact of agricultural policies. Not only does the model produce the World Agricultural Outlook (OECD-FAO 2010), but it was also used to estimate market impact of biofuels production and land requirements to cover biofuels demand (OECD 2006). On the other hand, the Food and Agricultural Policy Research Institute (FAPRI) have developed a set of multi-region models including the dairy, coarse grains, oilseeds, rice, livestock and sugar models. These models can be linked between each other to analyse area, production, usage, stocks, prices, and trade of a set of products in a global scale.

Global equilibrium models have focused on assessing international indirect LUC. While it is pertinent to use a worldwide scale model for this purpose, national specificities are very simplified. National scale models are less common. The main advantage of their application is that we gain a detailed description of the sector under study and its implications in the national economy. However, several simplifications need to be done as physical system boundaries are fixed at the nation’s border. Examples of national equilibrium models include a general equilibrium model used to estimate the role of multi-product crops for bioelectricity generation in Poland. The competition between agriculture and biomass for limited land resources was studied and changes in this production share have induced significant changes in land allocation (Ignaciuk and Dellink 2006).

In ABMs scale is generally limited to local/regional models. This reduces their applicability to estimate the impact of national biofuel policies. For instance, a spatial dynamic agent-based model was used at the county level to assess land-use competition for bioenergy crops (Scheffran and BenDor 2009). As they focus in individual decision making processes, aggregations at the national level may not be desired. In studies conducted by Wu *et al.* (2007), an integrated modeling framework is used to simulate individual agricultural producer decisions on sown areas of major crops in a global scale. The integrated modeling framework links the EPIC, the IFPSIM and a multinomial logit model of crop decision choices. This is a first attempt to account for local drivers in global models.

In the biofuel sector, SD models have been applied mainly at the national scale. Several SD models are being used to simulate the biofuel supply chain in the US (Bantz and Deaton 2006; Bush *et al.* 2008; Malczynski *et al.* 2009; West *et al.* 2009). Alternatively, studies by Sheehan (2009a; 2009b), have addressed the global LUC induced by cellulosic bioethanol production in the US. The model does not account for economics and focuses mainly on estimating the GHG emission balance of US ethanol, including direct and indirect LUC. Models at the regional scale however, have also been developed. In a study by Szarka *et al.* (2008), a SD model is used to assess the impact of bioenergy production of GHG emissions at the local/regional level. An advantage of SD models is that the modeler can choose the scale to fit its research purposes. This is possible because data requirements are less strictly needed, as the modeling technique focuses on describing the behavioural patterns of the system.

2.5.2. System boundaries

The choice of scale is associated with the selection of the system boundaries. The system boundaries can be fixed depending on the processes that are included in the estimation of the biofuel GES. In the case of land-use changes, these processes may include direct LUC from the supply of land for the feedstock production and indirect LUC from the displacement of other land-uses or uses of the biomass. The system boundary of the model can derive from the biofuel policy. In the EU-RED for example, only GHG from direct LUC are included. On the other hand, in the US-RFS both processes are included.

Concerning biofuels impact on land-use change, most equilibrium models have been used to assess indirect LUC (Edwards *et al.* 2010b). They account for land-use displacements in other countries due to increased demand for biofuel feedstocks in countries/regions with a biofuel mandate. Global agricultural commodity markets make that indirect land-use change may occur in other countries, which justifies the choice of a global model. On the other hand, if only dLUC GHG emissions are included a more detailed national scale model may be preferable. Indeed in the EPA approach a global general equilibrium model is linked to a national partial equilibrium model of the US agricultural sector. Models linkage is helpful in expanding the system boundaries, while preserving the integrity of the original models.

Accounting for the impact of co-products production may also required a global approach. Co-products from biofuels production such as soybean meal and DDGS can be used as animal feedstock substitutes. These substitutes can be available in different production regions generating LUC elsewhere. Consequently, national scale models can be adapted to deal with biofuel policies that focus on promoting a particular biofuel pathway while global models can be used to estimate the international consequences of increased co-products availability. Taheripour *et al.* (2008), for example, used the GTAP model to analyse the impact of co-products on LUC at the global level.

In SD models the linkage to international markets has been treated in a simplified way, as they focus on selected biofuel supply chains. A common feature of these models is their theoretical basis on the Sterman’s generic commodity market model (Sterman 2000). The Sterman’s model simulates the dynamics of supply and demand for a given commodity based on its price. The price of the commodity depends mainly on the inventory coverage and the demand level to be satisfied. Several recent studies (Jahara *et al.* 2006; Shri Dewi *et al.* 2010), for instance, applied the generic model to study biofuels demand impact of the Malaysian palm oil industry. This SD model focuses on the integration of local and international markets through price linkages and simulating the effect of price changes on production, stocks and exports of palm oil. An economic model of Malaysian supply and demand of palm oil is used as the main structure to formulate the SD model.

A limitation of these models however, is their focus on simulating business cycles disregarding the effect of other drivers of supply and demand of the commodity. On the other hand, price linkages between global food markets and food-energy prices are addressed by Kim (2009). Kim focused on a global scale modeling of the cereals and energy market accounting for the effect of external factors. The model included exogenous variables based on scenarios of oil price and world economic growth that partially drives the dynamics of the system. The model allows forecasting global production, consumption, and stock of food and energy markets by 2030 (Kim 2009). Price linkages between crude oil, biofuels and food products are also addressed by Sandvik and Moxnes (2009) in order to simulate the impact of price interactions on long-term food security. The expansion of the model boundaries to account for global issues in SD models however led to a simplified representation of the national biofuel industry.

2.6. Spatial and time dynamics

2.6.1. Accounting for spatial patterns

Spatial representation is a key feature in modeling LUC due to the correlation between different land-uses and the spatial heterogeneity of land. Current models have linked agro-ecological classification of land-uses to economic models or have linked other spatially explicit models to account for spatial patterns of land-use change. A first attempt to account for spatial patterns of biofuel crops was developed by linking the LEITAP (a modified version of GTAP), the IMPAGE and the Dyna-CLUE models (Hellmann and Verburg 2010, 2011). The integrated model constructs a spatially explicit, multi-scale, quantitative description of land-use changes through the determination and quantification of location factors of land-uses based on the actual land-use structure. The approach determines the location of crops expansion and consequently, the direct land-use effects of biofuels.

Spatial patterns are also being introduced in economic models by including spatial features in economic variables. This is the case for example, for the representation of land rent based on differences in land productivity (van Meijl *et al.* 2006). Several improvements have also been made in modeling land heterogeneity in the GTAP model including the disaggregation of land by agro-ecological zones at the country level (van Meijl *et al.* 2006; Golub *et al.* 2008; Hertel *et al.* 2008a; Lee *et al.* 2008; Monfreda *et al.* 2008). In this context, the GTAP model was used to evaluate land-use changes due to crops consumption (Kløverpris *et al.* 2008b). The modeling framework was applied to estimate land-use impacts of wheat consumption in Brazil, China, Denmark and USA (Kløverpris *et al.* 2010). Other studies (He *et al.* 2005), have focused on integrating system dynamics with spatial explicit models in order to account for the space-time dependency of land-use change in biofuels production.

The representation of spatial heterogeneity of biofuels feedstock and crops productivity at the national and global scale is still rough. Great work has been done to geo-referenced agricultural and forest land-use data. Average harvested area and yield values for 175 individual crops at the global scale are available from Monfreda *et al.* (2008). Data has been further disaggregated in agro-ecological zones. This information is useful to model feedstock location patterns. Several improvements have been also done to improve the disaggregation of national data. In the FAPRI model for example, land heterogeneity is specifically detailed for the US and Brazil. Most developments at the national level however, rely on global land-use databases. As their resolution is rough, classification of land-uses sometimes do not match the real landscape. This is a problem for estimating the impact of biofuel policies on LUC due to biased induced by a misclassification of land-use data.

2.6.2. Modeling of time dynamics

Time dynamics are differently represented in the reviewed models. They can vary between comparative-static, recursive-dynamic or fully inter-temporal models. The model choice influences the prediction capacity and its adequacy to evaluate different effects in time. While some models are more suited to assess long term impacts others may be preferable for short to medium term analyses. Some models have been applied because they were easily adapted to address biofuel policy issues, but without a reflection on their adequacy to treat problems at different time scales.

A distinction can then be made about the short and long term effects of biofuels production. Actors may produce a short term effect that generates conjectural market changes that then disappear over a period of time. Structural changes, on the contrary, are typically observed in the medium or long term. For instance, biofuels production may significantly increases commodity prices in the short run that may be also associated with stocks availability and the influence of meteorological conditions. In the long term, high commodity prices may encourage new producers to come into business, increasing supply and reducing prices.

Static models assess the reaction of the economy at only one point in time. They express results as a relative change between two alternative future states (typically with and without the policy shock) for a base year economy (initial year of the model). The GTAP model version used to address the impact of biofuel policies on land-use change is a comparative-static model that solves equations for the year 2020, with a base year in 2007 economy. Even thought a recursive dynamic version of GTAP has been developed (GDyn) only the comparative-static version has been applied to assess the impact of biofuel production on land-use change.

Recursive-dynamic models solves for two successive years, taking as base year the previous period. Inter-temporal or fully dynamic models applied the same approach, but the time step is significantly smaller to capture the dynamics of the change. The EPPA model solves in a recursive 5 years interval, modeling the 1997 world economy from 2000 to 2100 and is more suited for long-term analyses. FAPRI is a recursive dynamic model that solves simultaneous equations each year, more suitable for short-medium analysis.

Global equilibrium models used to assess biofuels impact on land-use change are generally static or recursive dynamic. The representation of the economy in a static state may be less suitable to study developing or transition economies that are undergoing rapid and substantial changes such as the fast grow biofuel sectors. Developing and transitional economies are expected to play a significant role in biofuels production due to the availability of land, feedstock and economic development goals. Moreover, investments in biofuels research are feeding technological development in this area. Consequently, new biofuels technologies are emerging that reduces competition for land. This dynamic innovation process is poorly accounted for in current equilibrium models.

Actors’ responses can differ in the short and long run, as time also affects decision making. Equilibrium and optimisation models assume that actors are completely capable of responding to changes. For instance, they assume producers respond immediately to biofuel mandates or that unmanaged lands are immediately transformed into an economic use. They ignored structural barriers and institutional impediments constraining supply. When crop price changes, for example, actors are not capable of immediately responding to this change. This is especially important when it implies taking a planting decision. Farmers need time to perceive this change in price, time to decide on the crop to be sown and time to grow and harvest the crop. Accounting for these time dynamics can lead to delays on feedstock supply influencing biofuel producers' capability to respond to the biofuel policy. While actors need time to adapt their expectations and take actions, policies need time to be design and implemented. Time delays can be very harmful to the biofuel industry, as market conditions change very fast. These aspects are essentially treated in system dynamic models.

Land-use change patterns are also variable over time. Land conversions between managed lands, for instance, are typically short terms conversions. It is relatively easy to convert pastureland into cropland. Expansion into managed land requires a longer period to occur, for example, the expansion of the agricultural frontier into forest land takes a considerable number of years until land is effectively used as cropland. The LEITAP model, for example, focused on the analysis of long-term land-use dynamics due to biofuels introduction (Woltjer *et al.* 2007; 2008), assuming immediate conversion of land-uses. The time dependency of land-use conversions can be better addressed in system dynamic models, as delays in decisions are better represented.

In the case of GHG emissions from land-use change, accounting for time is a central issue. The conventional approach to assess GHG emissions from land-use change is based on a "straight-line amortisation" approach. GHG emissions from carbon stock changes in land due to feedstock expansion are equally divided over time, assuming a fixed period during which the feedstock is assumed to be cultivated in a certain type of land. In the EU-RED for instance, this time period is set at 20 years. However, according to O'Hare *et al.* (2009), the global warming intensities of crop-based biofuels and fossil fuels differ not only in amount but also in their discharge patterns over time, which implies discounting emissions in order to take policy decisions about the impact of biofuels production on land-use change. De Gorter and Tsur (2010) supported this view, by proposing a greenhouse gas (GHG)-reduction standard that accounts for a range of discount rates and an upper bound on the GHG payback period. Then in the EU-RFS, GHG emissions from LUC are discounted to account for the present consequences of biofuel production on LUC.

2.7. Concluding remarks

The introduction of GES regulations for biofuels trade in developed countries encouraged the modeling efforts to assess the impact of biofuel production on land-use changes and GHG emissions. Critical modeling choices should be made to perform such analysis that results on modelling approaches suitable for different types of analyses. Models integration seems to be the way to account for the complex structure of this system. For the purpose of this research, the conclusions of the benchmark of the reviewed models and the choice of key modeling issues are summarized as follows.

Most of the models currently used are adapted from previous works as they were developed for other purposes. This implies some limitation in representing the biofuel sector and assessing specific biofuel production pathways with respect to the fulfilment of GES thresholds. For the purpose of this research, an integrated modeling framework is specially designed. The scope and objective of the proposed modeling approach is focused on the assessment of the biofuel export potential under GHG emission constraints, accounting for GHG emissions from direct LUC.

Given the focus of the modeling approach on assessing the Argentinean potential as a biodiesel exporter, biofuel policy objectives are not explicitly represented. Consequently the research abstains from any policy recommendation. Policy instruments on the other hand, are explicitly represented as they may play a major role on the dynamics of the domestic biodiesel industry. A key limitation of previous studies is their focus on biofuels mandates, disregarding other agricultural and economic policies where the biofuel industry is developed. In this research the main policies at the country level that affect the biofuel export potential are identified. The modeling approach accounts for the specificities of the domestic biodiesel policy as well as accompanying policy measures. Other domestic policy instruments affect the biodiesel supply and policy constraints imposed by biodiesel importing countries are explicitly represented.

The level of aggregation of actors would account for the specificities of the Argentinean biodiesel policy. In this context, provided that the Argentinean biodiesel policy supports small and medium biodiesel producers, firms need to be disaggregated, at least in the biodiesel sector. For this research, a biodiesel supply chain structure is assumed based on interconnected and aggregated profit maximising firms that respond to government policies, production costs and international prices. Compared with other models of biofuels supply chains, the modeling framework specifically addresses biodiesel supply allocation between the domestic and international biodiesel markets and also between firms' supply based on a disaggregation of the biodiesel sector in two aggregated firms.

A national scale model is sufficient given the scope of the research. While this allows a more detailed representation of the biofuel supply chain and the regional specificities in the feedstock production phase, the link to the international market needs to be treated in a simplified way. In this context, the impact of co-products and the effect of biodiesel production on indirect LUC need to be left out of the analysis. Global equilibrium models have focused on the worldwide impact of biofuel production, linking national and international markets. In this modeling approach this issue is treated in a simplified way by assuming exogenous world prices and final demands in return for domestic goods.

Spatial patterns need to be considered especially in the feedstock production phase. Land heterogeneity, land expansion constraints and regional specificities on feedstock production seem to be the key factors affecting land supply. Time dynamics are considered including the time horizon of the biofuel policy and the evolution of international markets. Delays in decision are explicitly modeled for goods supply and land conversion decisions. These issues have received little attention in current approaches to deal with the impact of biofuels production on LUC.

3. Market analysis of soybean and value-added products

3.1. Characterisation of soybean products

3.1.1. Demand drivers

A common characteristic of agricultural crops is the derived nature of their demand (Schnepf 2006). Demand for soybeans arises almost entirely out of the demand for the two processed products. Soybeans are mainly crushed to produce soybean oil and soybean meal. Food and other uses of whole soybeans remains a small share of total soybeans' utilisations. In 2010, for instance, 71% of world soybean production was diverted to soybean oil and meal production, while only 5% was diverted to food use and 6% to other uses, with the residual 16% remaining as stock (FAPRI 2010b).

Processed soybeans are the largest source of protein feed and vegetable oil in the world (USDA 2011b). While soybean meal demand depends mainly on market conditions in the feed grain sector, soybean oil is affected by market conditions in the edible oil sectors, both in the domestic and international markets (Susanto 2006). Soybean meal is the world's most important protein feed due to its high content of crude and digestible protein and low fiber content, including nearly 65% of world supplies (Soyatech 2008). Livestock feeds account for 98% of soybean meal consumption, being almost the single utilisation of soybean meal, as feed grain in the poultry and pork industries. Additional uses include human foods such as bakery ingredients and meat substitutes (USDA 2011b). Similarly, soybean oil is the world's largest source of vegetable oil. Soybean oil accounts for about two-thirds of all vegetable oils and animal fats consumed in the world. It is mainly used in salad and cooking oil, bakery shortening, and margarine, as well as in a number of industrial applications (Houck *et al.* 1972b). In recent years, its use as feedstock for biodiesel production has significantly grown, becoming an additional driver of soybean oil demand.

Biodiesel demand has significantly increased in recent years, mainly due to the implementation of biofuel policies in several countries. Demand for biodiesel is mainly driven by biodiesel consumption mandates (Ponti and Gutierrez 2009) and biodiesel is primarily used as fuel in different blending proportions ranging in average from 5 to 20% depending on the type and level of the mandate (Sorda *et al.* 2010).

Oilseeds and feed grains' total demand is mainly influenced by macro-economic variables. Population and income dynamics in consuming countries are largely responsible for the increased demand of oilseeds and feed grains (Schnepf 2006). In the international market, import for whole oilseeds in consuming countries depends on the deficit between a countries' domestic oilseed production and its consumption. Divergent requirements for protein meal and vegetable oil, as well as constraints on domestic processing capacity, determine the amount of oilseed products that a country will import (Schnepf 2006), defining the required volume of trade in the international market.

On the other hand, the residual export demand faced by a producing country depends mainly on the countries competitiveness, which is, the ability of a country to supply a good to the international market at a competitive price. Competitiveness depends, among others on production, transport and marketing costs, macroeconomic policies, sector-specific policies, infrastructure and the supporting institution. Export shares and growth trends also depend on domestic demand, relative returns to other crops, and other conditions (Smith 2009).

3.1.2. Substitutes

The share of soybean on oilseeds demand is driven mainly by consumer preferences for a particular type of oil or meal and the price of soybean products relative to substitutes (Soyatech 2008). Soybean is categorised as oilseed together with palm kernel, rapeseed, sunflower seed, cotton seed, and canola, among the main produced and traded oilseeds. Most of these crops, when crushed for their oil also yield high-protein meals that are widely used in livestock and poultry rations. As a result, most of them are relatively close substitutes and their prices are strongly correlated (Knipscheer *et al.* 1982).

In the international market, palm oil is the main substitute of soybean oil. Worldwide, soybean oil is still the largest source of vegetable oil. However, the rapid growth in palm oil production and the relatively low domestic demand in producing countries have driven the increment in palm oil imports in several countries (OECD 2006). In the domestic markets, soybean oil substitutes differ among consuming countries. In the EU, for instance, rapeseed oil is domestically produced and the main substitute for soybean and palm oil imports (Ponti and Gutierrez 2009).

The feed grain market allows for a more diversified availability of soybean meal substitutes (Knipscheer *et al.* 1982). Livestock feed rations are produced from a mix of protein sources, including among others corn, fish meals and rapeseed meal. In recent years, dried distillers' grains with solubles (DDGS), a co-product of corn-based ethanol production has gained attention as a substitute of soybean meal as protein feed (Lawrence 2006). The degree of substitution among these products depends mainly on the protein and fiber content of each product and the relative prices of these products in the market (Vandenborre 1966).

In the biodiesel market, fossil diesel is the main biodiesel substitute as fuel for transportation. However, technical constraints limit pure biodiesel utilisation without adapting fuel engines (Sims *et al.* 2008).

3.1.3. Production technology and factors

Soybeans are mainly produced in good agricultural land using a variety of agricultural inputs. The key production factor however is land. Soybean yields vary in average between 1.5 and 4.5 ton/ha, depending on land productivity, cultivation methods and inputs applied (USDA 2001). Soybeans compete for agricultural land mainly with rapeseed, sunflower, corn and wheat. Among these crops, corn requires basically the same growing conditions as soybeans. This agronomic characteristic, among other factors, may explain the tight relation in land supply dynamics for both crops. In the US for example, due to the increased corn prices in 2007/8 corn acreage increased by 11 Mha while soybean area has been reduced by 13 Mha (Soyatech 2008).

Two different oilseed-processing methods are applied in the crushing industry. The common procedure is to use hexane gas in a solvent-extraction method to separate the oil embedded in the cell structure of the beans to produce soybean oil and meal. The second process, mechanical crushing by beans pressing, is much less efficient. Solvent extraction, consequently, is the primary method used by large soybean crushers (Soyatech 2008). Soybean oil and soybean meal are joint products and obtained simultaneously in rather fixed proportions in the processing operation (Ryan and Houck, 1976). On average, each ton of crushed soybeans yields 0.2 and 0.8 tons of soybean oil and meal, respectively (USDA 2011b). Soybean meal is the most valuable component obtained from soybeans, ranging from 50 % to 75 % of the soybean value (Houck *et al.* 1972b). Soybean oil, on the other hand, has generally a smaller contribution to the value of soybean, as it constitutes around 20 % of soybean's weight (USDA 2011b).

Biodiesel production technologies vary depending on the type of feedstock. Biodiesel is mainly produced from rapeseed in the EU-27, from soybean in the US, Brazil and Argentina and from palm oil in Malaysia and Indonesia. Transesterification with methanol is the traditional process to convert vegetable oils into biodiesel (Rajagopal and Zilberman 2007). In average, 1 ton of soybean oil yields 0.96 and 0.1 tons of biodiesel and glycerine, respectively. Glycerine is a co-product from biodiesel production that is used mainly in the pharmaceutical industry (Jungbluth *et al.* 2007).

3.2. Supply, demand and trade patterns in the international market

3.2.1. Main market players

In the international market of soybean products (soybeans, meal, oil and biodiesel), the supply side has been highly concentrated. Production and exports have been dominated by several countries (Table 3-1).

Major soybean producers include the United States (US), Brazil and Argentina which combined have accounted for nearly 80% of global production in 2010 (USDA 2011a). An important market development of the past decade has been the phenomenal growth of soybean production and exports by Brazil and Argentina. Together they currently account for about half of the world soybean export market, up from less than 15% before 1980 (Mattson *et al.* 2004).

On the other hand, two regions, the European Union (EU) and China, have accounted for nearly two-thirds of world imports. The EU is self-sufficient in vegetable oil, but its protein deficit still makes it the world's largest importer of soybean meal and second-largest importer of soybeans (USDA 2011a). An important demand-side market development has been the rapid growth of China's and India's economies which have spurred their domestic food consumption. China is now the world's leading soybean importer, and both China and India are among the world's largest vegetable oil importers. China, the US and the EU are the main consumers of soybean oil and meal. World crushing capacity is mainly concentrated in China, the US and Argentina.

The biodiesel market is also concentrated in few countries (Table 3-2). Biodiesel consumption is mainly covered by the EU (mainly Germany), the US, Brazil and Argentina, sharing 59%, 16%, 13%, and 7% respectively of the global biodiesel supply in 2010 (OECD-FAO 2010). Responding to the increasing world biodiesel demand many countries have jumped into biodiesel production. In 2010, 13 Mton of biodiesel have been produced (FAPRI 2010b).

Table 3-1. Main market players in the world market for soybean products.

Soybean			Soybean Oil			Soybean Meal		
Production	**kton/year**			**kton /year**			**kton /year**	
United States	90610	34%	China	9840	24%	China	43560	25%
Brazil	75500	29%	United States	8652	21%	United States	35978	20%
Argentina	49000	19%	Argentina	7265	17%	Argentina	29680	17%
RoW	49010	19%	RoW	15833	38%	RoW	66572	38%
Total	264120		Total	41590		Total	175790	
Imports								
China	52000	58%	China	1550	17%	EU-27	22900	40%
EU-27	13100	15%	EU-27	950	10%	Indonesia	2950	5%
Mexico	3550	4%	India	950	10%	Thailand	2340	4%
RoW	20630	23%	RoW	5678	62%	RoW	29301	51%
Total	89280		Total	9128		Total	57491	
Exports								
United States	40687	45%	Argentina	5000	50%	Argentina	28600	48%
Brazil	29880	33%	Brazil	1645	17%	Brazil	14150	24%
Argentina	8500	9%	United States	1452	15%	United States	8210	14%
RoW	12234	13%	RoW	1848	19%	RoW	8676	15%
Total	91301		Total	9945		Total	59636	
Crush				**Domestic Consumption**				
China	55000	25%	China	11347	28%	China	43260	25%
United States	44905	20%	United States	7530	18%	EU-27	32248	19%
Argentina	38000	17%	Brazil	5245	13%	United States	27896	16%
RoW	84393	38%	RoW	16812	41%	RoW	69229	40%
Total	222298		Total	40934		Total	172633	

Source: USDA (2011a)

Table 3-2. Biodiesel market players.

Production	**kton /year**		**Consumption**	**kton /year**	
European Union	7993	59%	European Union	8821	67%
United States	2187	16%	United States	2018	15%
Brazil	1749	13%	Brazil	1790	14%
Argentina	1175	9%	Argentina	513	4%
Malaysia	282	2%	Malaysia	55	0%
Indonesia	76	1%	Indonesia	14	0%
Total	13461		Total	13211	
Exports			**Imports**		
Argentina	662	65%	European Union	824	80%
Malaysia	227	22%	Japan	51	5%
United States	73	7%	Brazil	41	4%
Indonesia	62	6%	RoW	108	11%
Total	1024		Total	1024	

Source: FAPRI (2010b)

Export opportunities due to favourable production costs in producing countries and domestic supply constraints in consuming countries have strengthened biofuels trade among countries (Banse *et al.* 2007). Argentina and Malaysia are currently the main exporters with 65 and 22% market share, respectively of world biodiesel exports. Biodiesel imports are mainly from the EU. In 2010, 80% of world biodiesel exports were shipped to the EU (FAPRI 2010b).

3.2.2. Structure of the international market for soybean products

The international markets for soybean products have been dominated by several countries, notably the US, Argentina and Brazil on the supply side, and China and the EU on the demand side. This trade composition coupled with the tendency for industry concentration may potentially induce imperfect competition by which the dominating countries may use their market shares to influence prices in the international market. Moreover, each country involved in trade of soybean products has implemented sector-specific policies regulating the soybean complex that may support the oligopolistic structure of oilseed markets[22].

The perceived concentration of buyers and sellers in the international market of soybean products has stimulated several authors to analyse the market structure of the world soybean sector. Research by Pick and Park (1991), based on a firm pricing decision model, found that the world markets for soybean and soybean meal are competitive. Deodhar and Sheldon (1997) applied the new empirical industrial organisation (NEIO) approach to measure the presence of market power in soybean meal exports. The NEIO approach (Bresnahan 1982; Lau 1982) provides a general model of industry pricing based on models of imperfectly competitive, profit maximising firms where it is possible to model competition, monopoly, and all degrees of oligopoly. Similar to Pick and Park (1991), their study also suggests that the world export market for soybean meal was competitive. They found that the entry of Argentinean firms reinforced competition in the soybean meal international market. Finally, Susanto (2006) applied the NEIO approach to measure the degree of market power in the export market for soybean products. Similarly, he found that both soybean and soybean meal export markets are deemed competitive rather than behaving as a Cournot or any other forms of imperfect competition. This literature suggests that despite the oligopoly market structure of the world export market for soybean products, these markets seems to be perfectly competitive.

Following this discussion, the role of Argentina as a main player in the international market for soybean products is straightforward. In practice, if we assume that Argentinean firms seek to maximise profit and provided that 1) despite the large market share of Argentina in international trade for soybean product Argentinean firms behave as price takers and 2) other countries can substitute Argentinean production; then, Argentinean production patterns will depend partly on the evolution of international prices. Firms take the international price as given and decide on the quantity of soybean products to be supplied to the market depending on their supply schedule at this given price. The importance of this assertion is that given that land supply for soybean production in Argentina depends mainly on the derived demand for soybean oil and meal in the international market, different land-use change patterns can result depending on the evolution of international prices of soybean products.

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[22] Refer to Susanto (2006) for a review on firms' concentration and government policies in the international market for soybean products.

3.2.3. Projections of international prices for soybean products

The exploration of future trends in agriculture markets is mainly performed by World Agricultural Outlooks (Blanco-Fonseca 2010). These outlooks provide a consistent view on the likely evolution of global agricultural markets over some future time horizon and under a specific set of assumptions about exogenous drivers. The main exogenous drivers include population growth, technological change, and macroeconomic variables, such as GDP growth, inflation, crude oil price and exchange rates (Wisner *et al.* 2001). Typically, market projections are based on economic models calibrated with historical data and experts' judgment.

Several national and international institutions develop projections for agricultural commodity markets. Three institutions provide a global Agricultural Outlook every year: The Economic Research Service (ERS) of the United States Department of Agriculture (USDA), the Food and Agricultural Policy Research Institute (FAPRI), and the joint outlook of the Organisation for Economic Co-Operation and Development and the United Nations Food and Agricultural Organisation (OECD-FAO).

Analysing agricultural baselines for the period 2010-2020, all outlooks agree on the fact that the growth in the oilseeds sector is tightly linked to the population-driven increase in demand for vegetable oil for food use, the increased demand for biodiesel feedstock and the increased meal demand for feed. All outlooks project growth in production, consumption and trade of oilseeds and oilseeds oils. However, different data sources for exogenous macro-economic variables and different policy assumptions largely drive the quantitative difference in agricultural outlooks results. FAPRI projections, for instance, are in general 10% to 15% higher, given that OECD-FAO assumes deeper and longer economic slowdown (Blanco-Fonseca 2010).

Projections among different agricultural baselines however are difficult to compare. A limitation of the USDA Outlook is its focus on the US commodity markets and the lack of data on world commodity prices and biofuel markets. FAPRI and FAO-OECD provide different projections for international prices of soybean and value-added products (Figure 3-1). A limitation of the FAO-OECD baseline is that soybean oil and meal prices are not estimated, but rather included in an aggregate price for oilseed oils and meals. Additionally, FAO-OECD estimates give world and Argentinean export prices for soybean and value-added products. Presumably, the world price may indicate the good price at the designation and the Argentinean export price may indicate the FOB price at the Rosario port. The FAPRI baseline on the other hand, provide different estimates of world market prices depending on location (Decatur, Rotterdam, Central Europe, NW Europe, Illinois) and including different risk of loss transfers from a seller to a buyer (FOB[23], CIF[24]).

In any case, FAPRI and FAO-OECD project increasing international prices for soybean and value-added products. The evolution trend of world prices for soybean products however, significantly differ between oil and meal. Variations in the relative prices of soybeans, soybean meal, and soybean oil indicate that the forces affecting prices in the oil market move differently from their counterparts in the meal market (Figure 3-1). Ryan and Houck (1976), attribute this difference to the existence of different demand drivers for soybean oil and meal. USDA (2011c) indicates that economic growth and population increase in developing

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[23] Free on board: The seller would provide the goods at the seller's expense.

[24] Cost insured freight: The seller will bear the cost of shipping and insurance up to the designation.

countries are projected to boost demand for vegetable oils for food consumption and biodiesel production is also projected to increase. As demand for vegetable oils increases faster than demand for protein meals, vegetable oil prices rise faster than oilseeds and protein meals prices. FAO-OECD and FAPRI projections for soybean oil and meal prices also reflect this view.

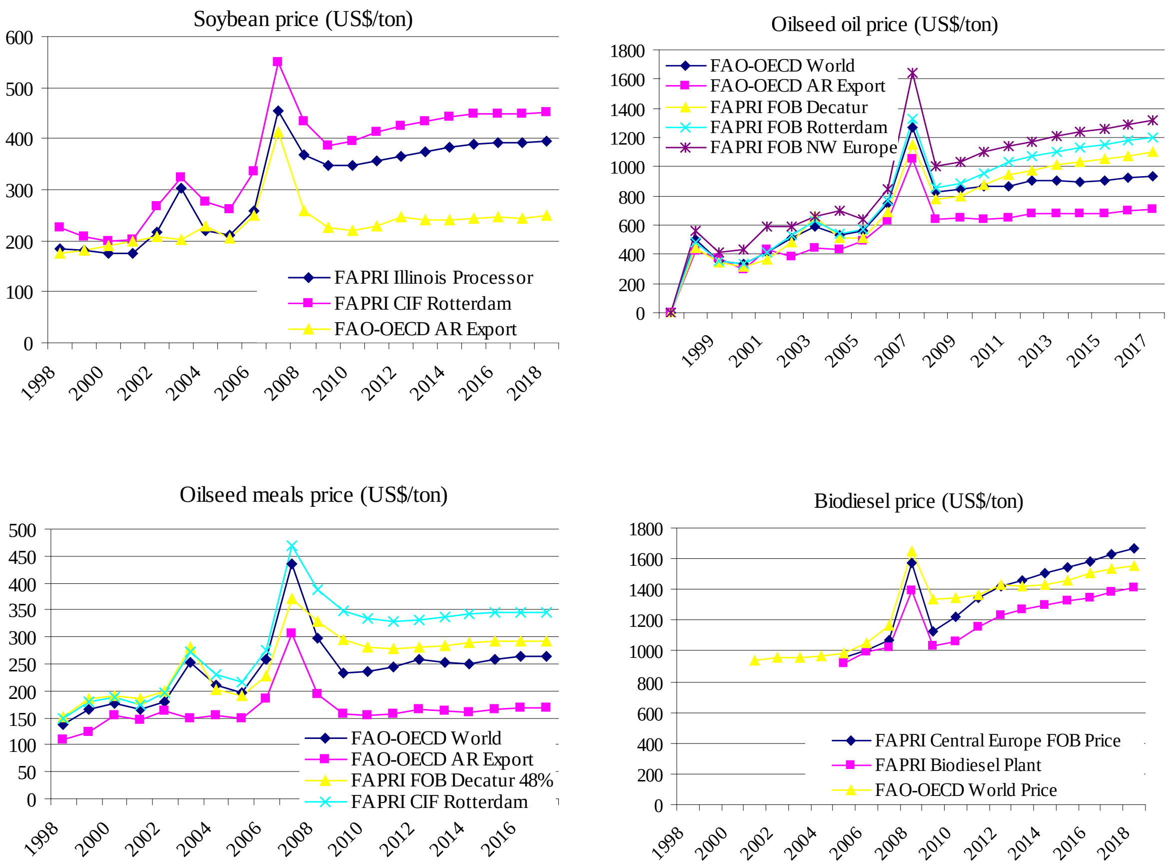

Figure 3-1.Soybean and value-added products world price projections.

Sources: FAPRI (2010b) and OECD-FAO (2010)

A special case is the world price projections from biodiesel. FAPRI trends for world biodiesel prices are higher than those projected by FAO-OECD. Edwards *et al.* (2010a) suggest that models assumed different scenarios about the demand for biodiesel, which may explain the different price projections. Moreover, as noted by Witzke *et al.* (2008), historical data on biodiesel production costs and technology efficiency are rather scarce given the recent development of the biodiesel industry. Consequently, parameter values concerning the calibration of biodiesel supply and demand functions may significantly differ among economic models.

3.2.4. Market trends for Argentinean soybean products

Different model structure, calibration of parameters, baselines, modeling assumptions and policy scenarios provide different trends of the market evolution for Argentinean soybean products.

A common feature of world market trend projections is that they are based on multi-region partial equilibrium models. A critical assumption in these models is market structure. Traditionally the perfectly competitive economic model has been assumed to assess trade patterns in agricultural commodity markets (van Tongeren *et al.* 2002) and the impact of biofuels production on land-use change and GHG emissions (Edwards *et al.* 2010b). Perfect competition is based on a set of assumptions including a large number of buyers and sellers, perfect information flow, zero transaction costs and no barriers to entry (Schnepf 2006). Firms have constant returns to scale and seek to maximise profit by deciding on the amount of homogeneous goods to be supplied to the market at a given price.

FAPRI and FAO-OECD Agricultural Outlooks provide projections of market trends based on the competitive firm model. However, despite assuming Argentinean producers (and other market players) are price takers from the international market, projections differ amongst each other. In the case of soybean and value-added products, significant differences can be observed for the export demand (and supply) projections for Argentina (Figure 3-2).

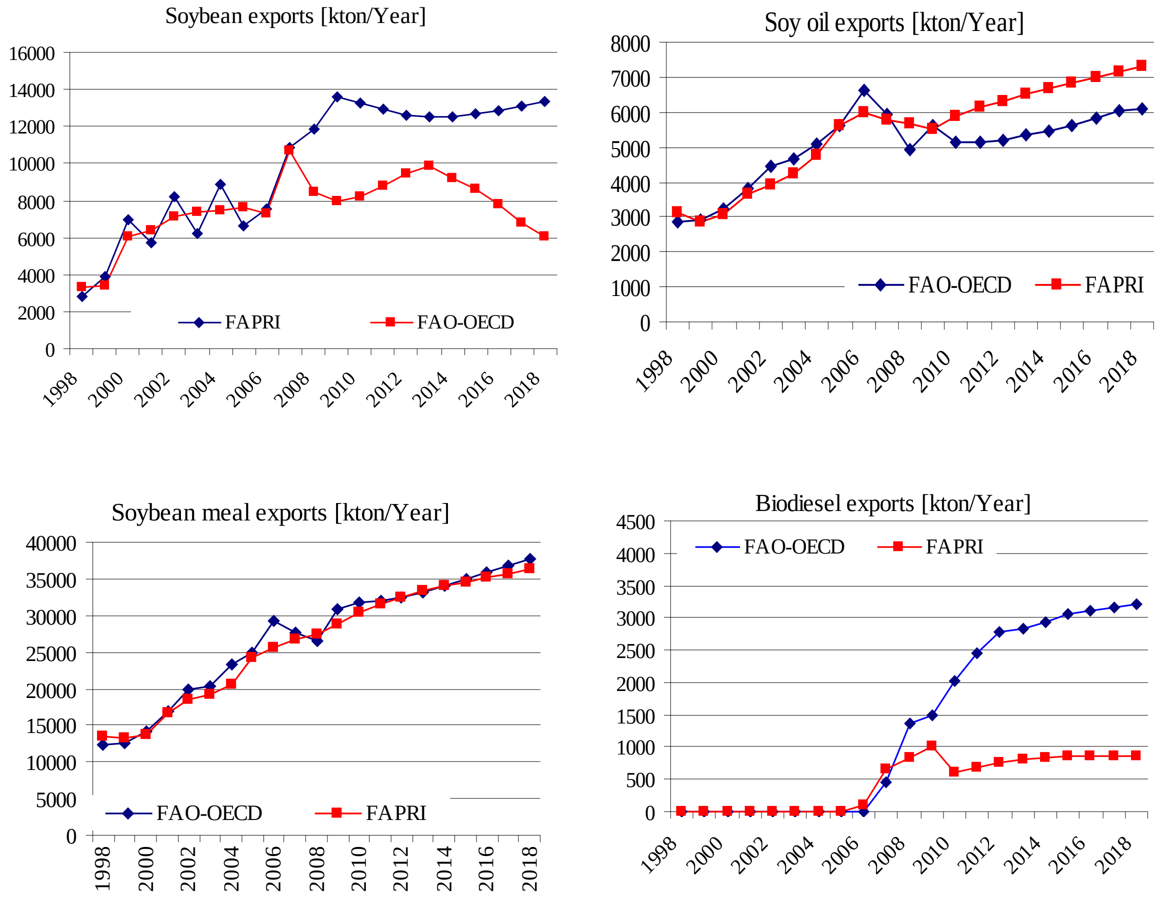

Figure 3-2. Demand projections for Argentinean exports of soybean products.

Sources: FAPRI (2010b) and OECD-FAO (2010)

FAO-OECD projects significantly higher exports for soybean and biodiesel than FAPRI (2010b) who state that policies encouraging domestic crush in China will increase soybean imports from this country. This view is supported by USDA projections (USDA 2011c) arguing that China will mostly import oilseeds for crushing rather than large amounts of oilseed meals and oils. This change in the composition of world trade by raising global import demand for soybeans rather than for processed product may partially explain the difference in Argentinean export demand projections for soybean and soybean oil.

Additionally, beside assumptions about the development of the crushing industry and the different world price projections among agricultural outlooks, modeling assumption and parameters may also explain this difference. Edwards *et al.* (2010b) for instance, argues that assumptions about trade in economic models yield significant differences among modeling approaches. In the case of trade, assumptions about goods substitution between domestic and import sources – the so called Armington assumption (Armington 1969) – can significantly change model outputs.

Both projections yield similar trends for Argentinean soybean meal exports, suggesting that assumptions about the evolution of soybean oil demand for food or biodiesel production is a major factor explaining the variability in soybean production and trade patterns for the Argentinean case. FAPRI (2010b) projects a 70 % market share for Argentina in the world export market for soybean oil and a 55 % market share in the export market for soybean meal.

In the case of biodiesel, significantly different projections are observed. While both outlooks indicate that Argentina will become the world’s leading biodiesel exporter, projected quantities of biodiesel exports largely vary between outlooks. FAPRI projects Argentinean biodiesel exports to reach 860 kton by 2020 (FAPRI 2010b), compared to FAO-OECD projections of 3220 kton by 2020 (OECD-FAO 2010). The assumed biofuel policy may play a major role in this case. For instance, while FAPRI assumed a 5% domestic blending mandate in Argentina, FAO-OECD projections did not account for the Argentinean blending mandate. This may result on higher quantities of biodiesel available for the export market.

Besides the influence of international markets, the characteristics of firms and the policy context play also a role on the market trends for Argentinean soybean products. The next section addresses these issues.

3.3. Market analysis for soybean products in the Argentinean context

3.3.1. Main market players in the Argentinean soybean sector

The Argentinean soybean-based biodiesel supply chain involves agricultural and industrial market players that include mainly the soybean producer, the crusher and the biodiesel producer.

Soybean producers are typically farmers with area ranging from 350 to 500 ha and where near 50 % of producers are land renters (Benbrook 2005). Agricultural census data indicates that small producers (up to 200 ha) have decreased in number and medium to large producers (200 to 2500 ha) have increased, leading to a concentration of soybean land (INDEC 2002). While the typology of farmers varies considerably among regions, in the case of soybean production, a special form of association is the sowing pool. They are investment funds that rent land for large-scale crops cultivation (Tomei and Upham 2009). Sowing pools, such as Los Grobo (130.000 ha), Adecoagro (225.000 ha) and El Tejar (150.000 ha) have grown very fast in recent years. An advantage of sowing pools is that because they are able to manage large areas, they can benefit from scale economies, producing soybeans at lower average costs. This economic advantage over “average farmers” allowed then to increase land rents. In 7 of the 11 campaigns between 1994 and 2005 soybean cultivation has produced higher rents than its main competitive crops (Aizen *et al.* 2009).

The industrial sector, on the other hand, is characterised by a high degree of firms’ concentration. While soybean producers are still large in number, only six firms control 85% of the soybean oil and meal production and exports. Processing capacity is concentrated in a few companies that control a large share of soybean crush (Lamers *et al.* 2008). Three national (Molinos Rio de la Plata, Aceitera General Deheza and Vicentín) and three multi-national (Bunge, Cargill, Dreyfus) companies account for 85% of the total soybean processing capacity. Their ability to set prices, however, in limited by the high dependence on international commodity prices. As domestic soybean oil and meal consumption is not significant, crushers demand relies almost exclusively on soybean oil and meal demand for the international market. Domestic soybean oil demand is low due to Argentinean consumer preferences for sunflower oil. Domestic soybean meal demand is low due to extensive livestock production system in Argentina.

Downstream and up-stream vertical integration is common in the crushing industry. Crushers typically participate on commercialisation and distribution stages downstream and on soybean production up-stream (Tomei and Upham 2009). Several joint ventures, especially between large crushers and foreign investors have led to the construction of large plants for biodiesel production. At the end of 2009, 26 firms supplied biodiesel for the domestic or the export market. However, 9 producers accounted for nearly 80% of the installed capacity (CADER 2009). Joint ventures give large producers a competitive advantage over small and medium firms. According to Joskow (2006), vertical integration of firms such as the case of joint ventures allows the joint firm to maximise profits by avoiding double-marginalisation[25]. CADER (2009) defined three types of producers depending on the firm size and the trade patterns of soybean oil as main feedstock for biodiesel production as follows.

Crusher-owned firms typically own large scale biodiesel plants with an average biodiesel production capacity of 232 kton/year. They are strategically located next to ports and have access to large quantities of feedstock providing them a competitive advantage in the biodiesel export market (van Dam *et al.* 2009a). Representative examples of large crushers account for Vicentin-Glencore (Renova), AGD-Bunge (Ecofuel), Dreyfus (LDC Argentina) and Molinos Rio de la Plata.

Non-crusher owned firms own medium to large plants with an average installed capacity of 200 kton/year. As they do not own the biodiesel feedstock, they buy soybean oil from oilseed crushers, generally through long-term feedstock supply contracts. Representative examples of non-oilseed crushers account for Unitec Bio, Explora, and Patagonia Bioenergy (Mathews and Goldsztein 2009). S

Small firms own small and medium plants with an average installed capacity of 35.6 kton/year. Generally, access to feedstock is done under tolling arrangements with large oilseed crushers. Representative independent companies account for Soyenergy, Biomadero, Derivados San Luis, Pitey and Energias Renovables Argentinas, among others (CADER 2009).

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[25] Refer to Joskow (2006) for a theoretical foundation of vertical integration strategies.

3.3.2. Policy framework in Argentina: Biodiesel and accompanying policies

Several policies regulate the Argentinean biodiesel industry. The biodiesel domestic market, for instance, is particularly framed by government policy instruments. The biofuels law (SyCDNA 2006) sets a 15 year volumetric mandatory blending of biodiesel in fossil diesel domestic consumption. Starting in January 2010, the mandate obligated local refineries to blend 5% (vol.) of biodiesel in fossil diesel. The blending target was increased to 7% (vol.) in July 2010 (SE 2010b) and is expected to be increased to 10% in 2011 (CADER 2011). Resolutions 7/2010 and 554/2010 determine supply quotas for biodiesel producers supplying the domestic market (PE 2009; SE 2010a). Biodiesel supply quotas are assigned by the government, in agreement with domestic biodiesel producers, to assure that *s&m* firms supply at least 20% of the total biodiesel domestic demand. Additionally, the government defined a *cost-plus pricing* policy for biodiesel supply to the domestic. The price at the biodiesel plant is based on average production costs of *s&m* firms and a *mark-up* profit of 28 US$/ton that “assured a reasonable profit” for the biodiesel producer (SE 2010a).

On the other hand, biodiesel producers focused on the export market should face new restrictions from biodiesel importing countries. Specifically, environmental and feedstock production criteria stated in the EU Renewable Energy Directive (EU-RED), the main export market destination of Argentinean biodiesel (EC 2009). The EU-RED established that biofuels supplied to the European market in order to comply with the 10% mandatory blending of biofuels in transport fuels would assure a GHG emission saving of 35% compared with the fossil reference. Additionally, from 1 January 2017, the emission saving requirement is raised to 50% and to 60% from January 2018. Considerable efforts are being done by the Argentinean government to demonstrate the GHG emission saving of soybean-based biodiesel production (Muzio *et al.* 2008) and its compliance with the EU-RED.

In recent years, the Argentinean Government has implemented several polices in order to regulate agricultural commodities supply, especially affecting the soybean complex. Due to the Argentinean economic crisis in 2001, the Senate passed a law (Law 25.561 of Economic emergency) allowing the executive branch to take exceptional economic measures, including the setting of the currency exchange rate and the fixation of export taxes. Currency devaluation in 2001, from 1:1 (US$ parity) to 1:3.5 (1 US$=3.5$) generated a large increment in Argentinean exports, especially of soybean value-added products (Lamers *et al.* 2008).

The biodiesel supply chain is particularly affected by differential export taxes (DET). DETs are those in which the export tax on a processed product is lower than that on the corresponding unprocessed product (Bonarriva *et al.* 2009). The DET regime is frequently implemented as means to diversify exports and to develop a domestic processing industry (Deese and Reeder 2007). In the Argentinean case, *ad-valorem* DETs in the soybean industry are currently applied as follows: 35% to soybeans, 32% to soybean oil and meal and 20% to biodiesel. These values have historically changed significantly depending on government perception of market conditions. In 2008 for example, Resolution 125 intended to change the export tax regime to a mobile mode in order to adjust export taxes based on changes in world commodity prices (MEyP 2008). Export taxes are also applied in other agricultural commodities. Corn, wheat, sorghum and sunflower were taxed 25%, 28%, 20% and 32% respectively in 2010. Export taxes of these crops have significantly increased in 2007. These measures have created a socio-political crisis between the government and the agricultural sector which is still unsolved (Mathews and Goldsztein 2009).

Finally, sector-specific policies have also been implemented by the government to regulate the fuel sectors. Firstly, to stimulate domestic production import tariffs have being applied to fossil fuel imports. The government currently charges a 20% *ad-valorem* tariff on fossil diesel imports (FPC 2009). Additional policies control retail prices to final fossil fuels consumer. Resolution 295/2010, for instance, forced fuel retailers to move back to price levels of 31 July 2010, after Shell increased fossil fuel prices by 0.2 % - 1.8 %. Ceiling price policies are common in the refinery sector and also in the agricultural sector.

3.3.3. Argentinean supply response for soybean products and its effect on soybean land supply.

In the case of soybean products supply by Argentinean firms, market price depends mainly on international prices of soybean products given that almost all the production is exported. If Argentinean firms behave as competitive actors, they will take the international price as given and they will decide on the quantity of soybean products supplied to the market at this given price. Consequently, the supply response of Argentinean firms should consider the evolution of international prices[26]. This is particularly important for the soybean, soybean oil and biodiesel markets, where significant uncertainty seems to be linked to the evolution of their respective prices and trade patterns.

Additionally, the price transmission to Argentinean firms depends on government policies, such as export taxes, exchange rates and specific biodiesel policies. Firms also respond to production costs, which together with prices determine the profitability of the firm. Assuming that firms seek to maximise profit, in a perfectly competitive market, they will tend to produce at the level where marginal costs equal marginal revenue. For the Argentinean case, this means that taking production costs and government policies as given, firms will produce and sell as much as they want at this given price.

Structural factors driving demand for soybean products also play an important role. The total quantity of land diverted to soybean production depends on the projected evolution of the residual demand for soybean products. Economic theory indicates that farmers allocate agricultural land among competing land-uses based on relative land unit profits (Golub *et al.* 2008). In the case of soybeans, land unit profit depends among other factors, on the price that farmers receive from soybean production. As discussed, soybean production is mainly driven by the derived demand for soybean oil and meal in the export market. Consequently, a key factor to assess soybean land supply is the prevision of the export demand for soybean oil and meal which, in turn depends on the price crushers receive from supplying the joint products to the market.

Finally, the joint product characteristic of soybean oil and meal implies that soybean supply depends on the derived demand for soybean oil and meal. Given the relatively fixed proportion in output, relative values of soybean oil and meal depend mainly on the evolution of the market prices of these products. Therefore, the effect of biodiesel production in this context depends on how biodiesel demand affects the soybean international price and the supply of land for soybean production.

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[26] Accounting for this link implies that the evolution of international prices of soybean products will differ from those projected under the assumption of perfectly competitive markets.

3.4. Soybean production and impacts in the Argentinean context

3.4.1. Soybean land supply: Impacts on land-use change in Argentina

Soybean production in Argentina has significantly increased since 1970. Soybean acreage has expanded from 26 kha in 1970 to 15981 kha in 2007 at an annual rate of 19.1% (Aizen *et al.* 2009). In the same period, soybean production has increased from 27 kton to 47483 kton at an annual rate of 21%, due to soybean expansion area but also due to yield increments (from 1 ton/ha to 2.9 ton/ha) (Aizen *et al.* 2009).

Pengue (2003) stated that soybean area expansion took place by expanding the agricultural frontier as well as by replacing other activities. While the traditional area for soybean cultivation has been the Pampas region (Central region), the agricultural frontier has expanded to marginal areas for soybean cultivation, namely the North-Eastern (NE) and North-Western (NO) regions of Argentina (Grau *et al.* 2005).

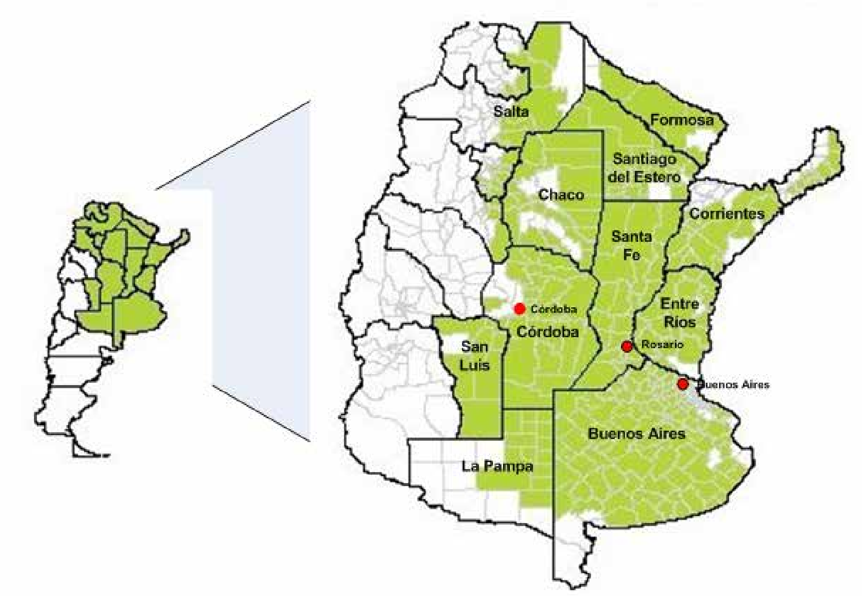

Figure 3-3. Distribution of soybean production area.

Sources: MAGPyA (2010).

Several studies have been conducted to assess land-use changes from soybean production in Argentina. Significant concerns have been raised about soybeans contribution to deforestation processes in the NO Argentinean region (Tomei *et al.*). Grau *et al.* (2008), for instance, have compared land-cover patterns and land-use and population trends in two critical NO Argentina regions where soybean expansion seemed to be a main driver of deforestation in dry forest/savannah ecosystems. They found that soybean production has contributed to the deforestation process in this area. Based on an analysis of Landsat satellite images, Gasparri and Grau (2009) further analysed changes in forest cover and landscape configuration in NW Argentina in four periods between 1972 and 2007. They argue that deforestation started in the 1970s as a result of technological changes and increasing rainfall, continued during the 1980s and 1990s in association to the sustained global demand of soybean, and was accelerated between 2001 and 2007 following the global increase in commodity prices, and the national currency devaluation. Their analysis concludes that direct land-use changes have occurred in the NO region at the expense of the sub-tropical dry forests, mainly the Yungas and the Chaquenean Forest: 118’000 ha have been deforested between 1998 and 2002 for soybean production in Chaco, 160’000 in Salta and 223’000 in Santiago del Estero (Grau *et al.* 2008; Gasparri and Grau 2009). CAPOMA (2009) suggests that deforestation for soybean cultivation, mainly in the Northern region has been a result of lack of control and regulation of land tenure. Further analyses by Grau *et al.* (2005) found that in the 1980s, high soybean prices stimulated deforestation. The introduction of soybean transgenic crops in 1997 reduced plantation costs and stimulated a further increase in deforestation. They conclude that if global trends of technology, soybean markets and climate continue, and no active conservation policies are applied, vast areas of the Chaco will be deforested in the coming decades.

Henry *et al.* (2009) addressed the impact of soybean expansion in agricultural cropland competition. They suggest that soybean expansion accounted for the shift from dairy farms and cattle breeding, the shift from annual crops production (mainly wheat, corn, cotton, sunflower, sorghum and rice) and the decrease in pastures rotation. The displaced activity, however, varies geographically, mainly between the traditional soybean cultivation area (Santa Fe, Cordoba, Buenos Aires and Entre Rios) and the marginal area (Santiago del Estero, Salta, Chaco, and Tucuman) (Grau *et al.* 2005; Henry *et al.* 2009). OEA (2009) compared National Agricultural Census data between 1988 and 2002 to explore soybean production patterns among different regions. In the Central region, dairy farms have been replaced by soybean plantations. Moreover, Coutinho *et al.* (2008) indicates that rotations with pastures have been reduced and displaced to the Northern part of Santa Fe. In Cordoba the same process has occurred mainly replacing pastures in the Pampas. In Santa Fe, 70% of the agricultural area is soybean, where soybean area has almost doubled the expansion of the agricultural area, suggesting that other activities have been substituted. According to OEA (2009) 60% of the soybean area expansion was done by first occupation, suggesting that crops rotation has been reduced. They state that soybean has replaced pastures, mainly perennial and other oilseeds, particularly sunflower.

Crops displacement for soybean production in the NO region have been addressed by Benbrook (2005) and OEA (2009), stating that soybean has not only replaced cotton plantations, but also other cereals. In the last 6 campaigns, cultivated area with cotton, rice, corn, sunflower and wheat have decreased by 83%, 44.5%, 25.5%, 23.8% and 14.5% respectively. In Chaco, 35% of soy area expansion from 1988 to 2002 has come from second occupation of soybean after cotton. In Salta, the agricultural area has increased 62% between 1988 and 2002, being soybean responsible for 71% of this expansion over the forest (OEA 2009). Moreover, pastures displaced from the Central (C) region may have partially induced the deforestation process jointly with direct soybean cultivation. OEA (2009) suggests that cattle heads have increased 34% from 1988 to 2002 in Chaco. Cattle heads in the NO and NE regions have largely increased in recent years mostly, by displacements from the Central region (Rearte 2007).

3.4.2. Soybean cultivation methods

Soybean production in Argentina has been influenced by significant technological changes that have reduced production costs and increased per hectare yield. For one hectare of soybean in the C region, the implantation cost have been reduced from 165.5 to 122.5 US$/ha while yields have increased from 2.3 to 3.4 ton/ha in the period 1990-2000 (Pengue 2003).

Technological improvements have began in 1970 with the introduction of wheat-soybean successions (double cropping) allowing intensifying land-use (Henry *et al.* 2009). This has reduced production costs, increased yields per hectare and facilitated management practices and production workload (Tomei *et al.* 2010). While first occupation soybean has provided higher yields, second occupation soybean has intensified land-use, producing two crops (wheat and soybean) in the same year. First occupation soybean is grown between October/November (sowing) and April/May (harvesting), corresponding to the optimal growing period for soybean in Argentina. The soybean cycle lasts for 6 months, and the land is then left and set aside during the winter (crop succession of set-aside land-soybean). Second occupation soybean is grown between December (sowing) and April/May (harvesting), after wheat. Therefore, soybeans of shorter growing cycle are used. Wheat is grown between June/July and December (harvesting) and soybean is sowed at the same time wheat is harvested. This allows having two crops per year on that land. However, as first occupation (FO) soybean is grown in the optimal period, higher yields are obtained compared with second occupation (SO) soybean.

Both first- and second-occupation soybeans are grown in monoculture as well as in rotation with corn or sunflower. However, no data was available of the proportion of each soybean type done in monoculture and in rotation. Soybean monoculture has led to lower yields. For instance, an estimate by Martellotto *et al.* (2001) indicated that soybean monoculture in Cordoba, yields 32% less than soybean rotation with sorghum in an average of 5 campaigns ((91/92 – 95/96). Soy-corn rotations increased soybean yield by 20% compared to soybean.

The adoption of no-tillage practice in the last decade has significantly reduced labour costs in soybean production, No-tillage cultivation currently accounts for 75% of the total soybean cultivated area (Pengue 2003). Compared with other crops, the adoption process was higher and faster (no-tillage cultivation accounts for 45%, 56% and 15% of wheat, corn and sunflower areas, respectively). The use of no-tillage method has reduced the operational workload for soybean cultivation from 4-5 workers per hectare to 1 worker per 500 ha in no-tillage RR-soybean production systems (Pengue 2003).

Finally, the third technological change was the introduction of genetically modified soybeans that were largely adopted by soybean producers. Transgenic varieties of corn and wheat, for instance, have taken 27 and 16 years to be 90% adopted. Comparatively, Round-Up Ready soybeans have been 99% adopted within 6 years (Tomei *et al.* 2010).

3.4.3. GHG emission balance of soybean-based biodiesel production

In the assessment of biofuels GHG emission balance a critical factor is the inclusion of GHG emissions from LUC. Land-use is defined as the type of activity being carried out on a unit of land. Six top-level land categories for greenhouse gas (GHG) inventory reporting are specified in the IPCC guidelines for Land-use, Land-use Change and Forestry (GPG-LULUCF), including forestland, cropland, grassland, wetlands, settlements and other land. Direct land-use change (dLUC) occurs when feedstock for biofuels purposes (e.g. soybean for biodiesel) displace a prior land-use (e.g. forest), thereby generating changes in the carbon stock of that land. Indirect land-use change (iLUC) occurs when the displacement of a previous activity or use of the biomass induces land-use changes on other lands. The displacement of current land-use to produce biofuels can generate more intense land-use elsewhere.

Table 3-3 shows GHG emissions estimates for soybean-based biodiesel and their associated annualised dLUC and iLUC emissions.

GHG emission estimates for soybean-based biodiesel have been provided by several authors. Significant difference can be observed among studies, especially regarding LUC GHG emissions. Several factors can explain these differences which may derive from different methodological assumptions in the LCA and the economic models, different inventory data, and different scenarios of biofuels demand and different geographical coverage. BPE (Panichelli *et al.* 2009), INTA (2008) and Greenergy (2010) studies, for instance, focused on soybean biodiesel production in Argentina. BPE only accounted for direct soybean expansion into forests, using average values between 2001 and 2005. The main difference on No LUC emissions from the INTA study relies on regional specificities and the use of different input values. While BPE used average values at the country level, the INTA study is specific for the Pampa region, the most productive region in Argentina. Similarly, the Greenergy study estimates iLUC emissions from soybean expansion into grasslands and croplands (mainly corn) in the Pampa region.

CARB and EPA analyses are specific for soybean biodiesel produced in the US in order to fulfil the Low Carbon Fuel Standard (LCFS) and the Renewable Fuel Rule (RFR2), respectively. The EPA study accounts for co-products credits and international iLUC. IFEU (Fehrenbach *et al.* 2008), EC/JRC (Edwards *et al.* 2010a) and IFPRI (Al-Riffai *et al.* 2010) studies mainly focused on the European context. High values in IFEU estimations are based on the risk adders approach. EC/JRC values are default values of the EU legislation. IFPRI values for iLUC emissions depend on trade liberalisation and peat lands accounting.

Table 3-3. Comparative LCA GHG emissions results for soybean-based biodiesel.

Study	**GHG emissions (gCO2eq/MJ)**		
	No LUC	**dLUC**	**iLUC**
BPE	40.32	80.65	-
INTA	23.2	-	-
Greenergy	42	-	10.9
EPA	31	-	42-68
IFPRI	-	-	75.40 -67.01
CARB	21.25	-	62
IFEU	75	924	243
EC/JRC	58	-	42

Due to differences on GHG LUC emissions estimations, carbon pay-back time (CPBT)[27] values for soybean-based biodiesel can also significantly vary. Panichelli and Gnansounou (2008) reported CPBT for soybean-based biodiesel ranging from -46[28] to 979 years. Gibbs *et al.* (2008) reported values of 1, 100 and 300-1500 years for soybean cultivated on degraded land or cropland, grasslands and forest, respectively. Fargione *et al.* (2008) reported values of 319 and 37 for soybean biodiesel production in Brazilian forests and savannas.

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[27] Number of years that a biofuel should be used to offset emissions from land-use change on feedstock cultivation.

[28] Negative CBPT implies emission savings.

4. Conceptual modeling framework

4.1. Biodiesel vertical market structure

4.1.1. Biodiesel supply chain structure

The biodiesel supply chain is defined as a set of actors and technologies involved in soybean production, soybean processing into oil and meal, oil conversion into biodiesel, biodiesel blending with fossil diesel and trading of these products in order to satisfy the intermediate and final demand of consumers.

The biodiesel supply chain is modeled and including three producers, namely, the soybean producer (*sp*), the crusher (*cr*), and the biodiesel producer (*bp*) (Figure 4-1). Despite many actors linked to the biodiesel supply chain, the modeling framework focuses on the interactions between producers in the soybean, crushing and biodiesel sectors. For simplicity, no intermediaries are accounted for in the supply chain, assuming that producers perform transactions directly with consumers, so that there are zero transaction and marketing costs. Five soybean products with increasing added-value are included, namely, soybean (*soy*), soybean oil (*oil*), soybean meal (*meal*), biodiesel (*bio*) and fuel blend (*fuel*).

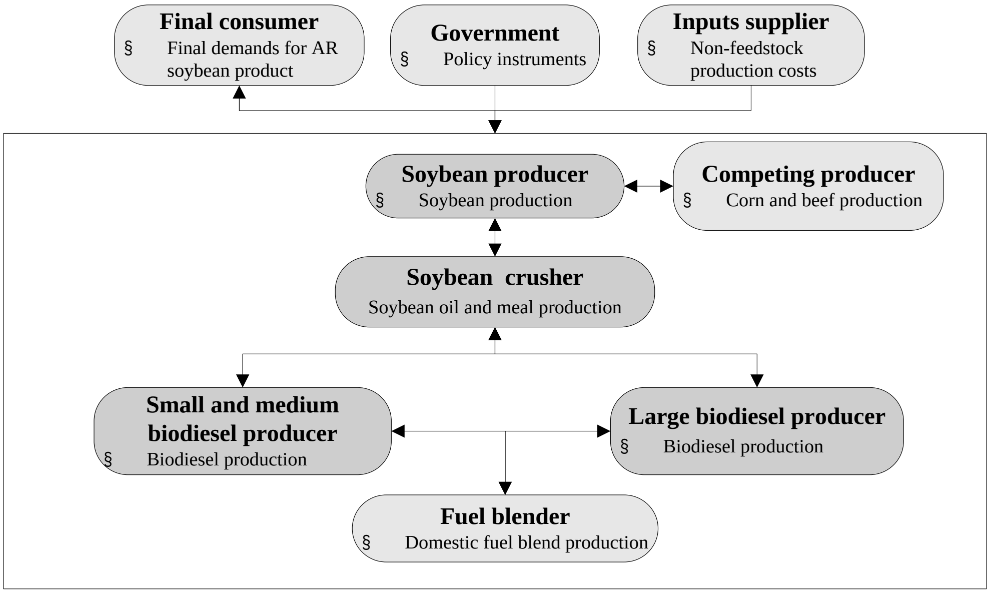

Figure 4-1. Actors' interaction.

Each producer, with exception of the biodiesel producer, is modeled as a single aggregated actor. For the purpose of this research, focused on the biodiesel export potential, a single aggregated actor is sufficient to represent the soybean, oil and meal sectors. In the biodiesel sector, however, two typologies of biodiesel producers are assumed depending on the firm size. Biodiesel producers, therefore, are classified in small and medium (*s&m*) and large (*lg*) firms. The firm size determines the cost structure and the conversion efficiency for biodiesel production.

Additionally, the model includes also other aggregated actors. The government (*gov*) defines policies which are exogenously introduced as constants. Government policies account for the main policy instruments regulating the soybean and fuel sectors. An aggregated final consumer (*c*) accounts for the Argentinean demand of each soybean product in the international market. An aggregated input supplier (*is*) is assumed to supply non-feedstock inputs, such as fertilisers, hexane and methanol. For the biodiesel domestic market, the fuel blend is assumed to be supplied by an aggregated fuel blender (*bl*). Finally, the model includes an aggregated competing agricultural producer (*cc*) including corn and beef production (Rozakis and Sourie 2005).

Producer models are built on classical economic theory of profit maximising firms. Supply of soybean products by AR firms is assumed to depend on the unit profit (net return) of AR producers. In the modeling framework, producers are assumed to respond to 1) the increased average return to capital of the crusher and of each biodiesel producer 2) the different land rent of each land-use type based on the different land productivities and 3) the rent for *s&m* biodiesel producers that result from the *cost-plus* pricing policy.

Supply of soybean products depends on the production function of each producer. In order to maximise profit the producer is assumed to decide only on the quantity of feedstock to be used to produce the firm output, given the production technology. To this end, for each aggregated producer a single input production function is assumed. The single input represents the quantity linkage among vertical producers in the biodiesel supply chain.

Formally, for each producer, the reduced form equation of the production function is given by:

$$q_o{}^p = (Y_o{}^p, q_j{}^p, q_i{}^p) \qquad \text{Eq. 4-1}$$

The index o denotes the firm output and the index p denotes the producer. Variable $q_o{}^p$ is the quantity of output supplied by the aggregated producer, $Y_o{}^p$ is a parameter representing technology and $q_j{}^p, q_i{}^p$ represent quantities of inputs. The index *j* denotes the feedstock used by each producer and supplied by each respective upstream producer. The index *i* denote other inputs and production factors which quantities are assumed constant. For the purpose of this research, land is assumed the only variable non-feedstock input. Table 4-1 specifies the production function variables of each producer.

Table 4-1. Variables specifications for each production function.

Producer (p)	**Input ($q_j{}^p$)**	**Technology ($Y_o{}^p$)**	**Output ($q_o{}^p$)**
Biodiesel producer (bp)	Soybean oil ($q_{oil}{}^{bp}$)	Biodiesel yield ($Y_{bio}{}^{bp}$)	Biodiesel ($q_{bio}{}^{bp}$)
Soybean Crusher (cr)	Soybeans ($q_{soy}{}^{cr}$)	Oil yield ($Y_{oil}{}^{cr}$) Meal yield ($Y_{meal}{}^{cr}$)	Soybean oil ($q_{oil}{}^{cr}$) Soybean meal ($q_{meal}{}^{cr}$)
Soybean producer (sp)	Land ($q_{land}{}^{sp}$)	Soybean yield ($Y_{soy}{}^{sp}$)	Soybeans ($q_{soy}{}^{sp}$)

Additional factors affecting land supply for soybean production accounts for land availability and productivity, soybean cultivation methods and managed land expansion patterns. While total land availability is assumed constant within the national territory, land productivity varies within the country. Land is disaggregated in four regions to account for regional patterns on soybean production. Therefore, the share of soybean cultivation methods and managed land expansion patterns are introduced as exogenous factors specific to each region and also assumed constant. Land expansion patterns determine the share of managed land expansion into unmanaged lands.

4.1.2. Supply and demand functions for soybean products

AR firms are assumed to behave as profit maximising firms acting in a perfectly competitive market. Competitive markets imply that producer economic profit is zero in the long run, so that the marginal revenue equals the marginal production cost. Supply functions then can be derived from the profit maximisation problem of each producer. Appendix 9.1 postulates the profit maximisation problem of each producer which led to the derivation of each supply function.

Supply of soybean products by AR firms is then assumed to depend on the average net return of each AR producer. In the case of the soybean producer soybean supply depends on the net return per unit of land. In the case of the crusher and the biodiesel producer, soybean oil, soybean meal and biodiesel supply depends on the net return on capital. Net returns are expressed as unit profits.

The AR firm supply function is specified as a constant elasticity function that depends on the producer unit profit. Formally, the reduce form of the supply function of the aggregated AR producer is given by:

$$q_o{}^p = q(g_o{}^p) \qquad \text{Eq. 4-2}$$

where $q_o{}^p$ is the quantity of soybean product *o* supplied by the AR firm and $g_o{}^p$ is the unit profit of the AR firm. The AR firm unit profit is defined as:

$$g_o = P_o \times (1 - w_o) - C_o \qquad \text{Eq. 4-3}$$

where w_o is the export tax, and C_o is the unit production cost, given the assumed technology.

Demand for soybean products is assumed to depend on the intermediate value-added demand by the downstream producer in the domestic market and the final demand by the consumer in the international market.

Intermediate value-added demand accounts for the quantity of feedstock demanded by the downstream producer in the biodiesel supply chain and account for:

- Biodiesel demand by the blender for fuel blend supply to the domestic market
- Soybean oil demand by the biodiesel producer for biodiesel supply
- Soybean demand by the crusher for oil and meal supply.

Intermediate value-added demands are modeled as constant elasticity functions depending on the average return to capital of each producer.

Final demand for AR soybean products depends on the demand level of the aggregated consumer in the international market. This demand level is defined as the market demand that is not met by other firms in the industry at a given price (Perloff 2008). The AR demand function therefore is the market demand minus the supply of other producers.

Long run changes in this demand level results mainly from structural factors[29]. Structural factors are mainly linked to the potential decisions of different consuming countries to produce part of their needs, the supply decisions of other producing countries and the emergence of new demand drivers. The annual demand for the AR soybean product on the international market is then adjusted by the evolution trend on structural factors.

For a given year, the international demand level for the AR soybean product is defined as follows. Once the interval of the potential volume of international trade has been set using structural factors, it is assumed that the aggregated consumer will maximise his utility within this interval by deciding on the quantity of soybean product demanded to the aggregated AR producer at a given price. Therefore, for each soybean product a demand function is specified as a constant elasticity function that depends on the international price of the soybean product and a demand shifter (Eq. 4-4).

$$q_o^c(P_o, d_o^c) \qquad \text{Eq. 4-4}$$

Variable q_o^c is the quantity of soybean product o demanded by the final consumer c to the aggregated AR producer. Variable P_o is the international price of the soybean product *o* and d_o^c is a parameter measuring exogenous changes in the international demand of this soybean product. Parameter d_o^c determines the main evolution trend of the demand for the AR soybean product, given assumptions on the international demand level and the supply of the soybean product by other producing countries. Production from other countries was set by scenario to keep the balance of total supply to the international market. This simplification allows accounting in a single function for structural factors affecting the international demand and supply by other producing countries.

The supply and demand curves for the AR soybean products can be calibrated based on historical price and quantity data, for instance, through econometric methods (Kennedy 1994). This approach requires consistent time series and several statistical tests to estimate parameters of the supply curve. Direct econometric estimation of supply functions has theoretical and empirical appeal but may be difficult to implement due to data and project resource limitations. In this research, therefore, the supply curve of each AR soybean product is estimated based on elasticity values and initial conditions given mainly in the literature.

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[29] Conjectural factors, on the other hand, may be linked to weather conditions, price peaks and possible substitution with other products. These factors tend to affect supply and demand in the short-run. Provided that LUC is a long term effect demand functions are modelled accounting for structural factors.

4.2. Linkage of AR supply to international markets

4.2.1. Supply response to international prices for AR soybean products

The procedure to determine the quantity of soybean product (i.e. soybean, oil, meal and biodiesel) supplied by the AR producer and allocated to the international market is defined as follows (Figure 4-2).

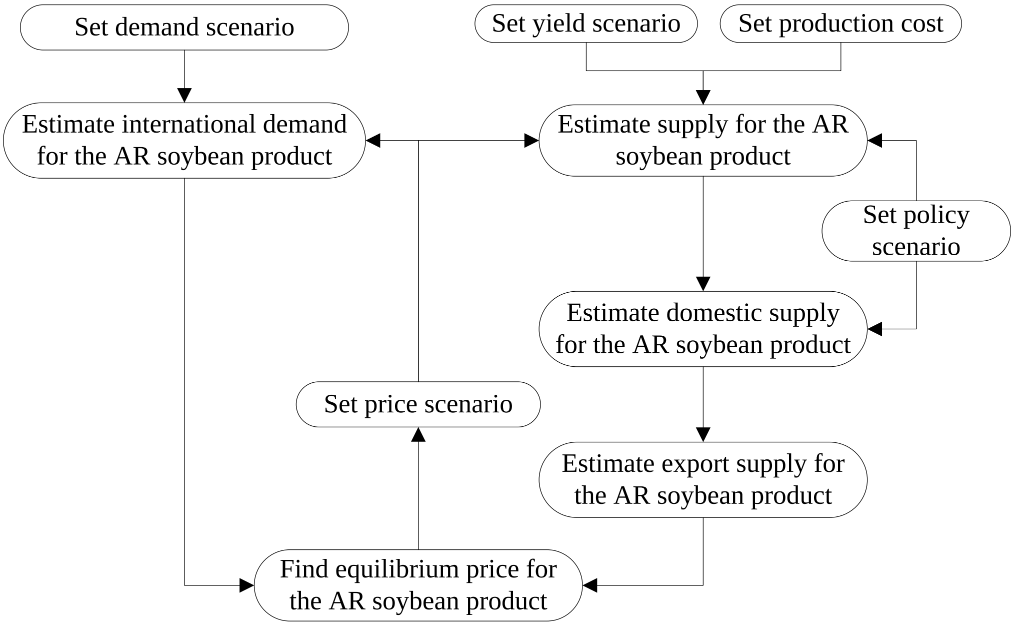

Figure 4-2. Soybean product supply: price adjustment procedure.

On the one hand, for a given year, the price of the soybean product in the international market is set by scenario. Formally, the international price of the soybean product is given by:

$$P_o = P_o(q_o{}^p, q_o{}^c c_o) \qquad \text{Eq. 4-5}$$

where c_o is the price trend scenario given the assumption made about structural factors affecting the international price.

For modeling purposes, the framework assumes that the aggregated AR producer acts in a perfectly competitive market. Consequently, the international price of the soybean product does not depend on the quantity supplied by AR firms, so that $P_o = P_o(c_o)$.In this case, each firm takes the international price P_o as given and decides on the quantity of soybean product $q_o{}^p$ to supply at this given price.

Different scenarios can be defined about the price evolution of soybean products based on assumed structural changes on the demand or supply side. For instance, the demand for soybean and value-added products and the adjustment of the production capacity to the new demand level can vary among countries depending on factors such as natural resources availability and government policies. Therefore different price scenarios can be made based on a consistent set of plausible assumptions about the evolution of those factors over time.

On the other hand, a supply curve of the soybean product for each aggregated producer is specified in Eq. 4-2. Assuming the policy framework, the conversion yield and the non-feedstock production costs are set constant, supply depends only on the international price of the product.

Then, given the international price of the soybean product (Eq. 4-5) and the supply curve of the aggregated AR producer (Eq. 4-2), the quantity of soybean product that the AR producer is willing to supply to the market at this given price can be found. For this given international price, the aggregated AR producer estimates its unit profit and adapts the quantity supplied taking into account its supply curve.

The quantity that is found is the total production level of the AR aggregated producer. With the exception of biodiesel, where different pricing policies are applied to the domestic and export markets, the allocation of soybean products among market destinations follows the law of one price. Therefore, exports of soybean products are given by the quantity produced minus the domestic demand. In the Argentinean case, the domestic demand is almost completely covered by the use of the product as input in industrial processes. The quantity of soybean product *o* exported by each AR aggregated producer *p* is then given by:

$$q_o^{\exp} = q_o^{p} - q_o^{va} \qquad \text{Eq. 4-6}$$

where q_o^{va} is the intermediate value-added demand by the downstream producer.

4.2.2. Formulation of scenarios

Once the relation between the international price and the supply by the aggregated AR firm is formalised, different scenarios can be assessed with respect to:

- The evolution of the international demand for each soybean product.
- The government policies in the Argentinean context.

In the first case, the projected evolution of the international demand for AR soybean products is defined by scenario. A number of long-term, slowly-evolving factors can affect this demand level. The values adopted for the evolution trends may describe any plausible future. For simplicity, evolution trends are assumed to reflect trends of market projections in Agricultural Outlooks. Market projections are based on assumed events such as changes in demand, supply and trade patterns in Argentina and its competitors for the selected commodities (Annex 9.5).

Scenarios of the evolution of international demands for AR soybean products are introduced by assigning values to the respective d_o^c parameter in each AR demand function, $q_o^c(P_o, d_o^c)$, which represent the trend evolution of the demand for each AR product by the aggregated final consumer (*c*).

Values of d_o^c are estimated based on the compound annual growth rate between two years, t_0 and t_n. The interpolation of the values between t_0 and t_n is undertaken assuming that the trend is exponential. This approach has the advantage that alternative scenarios can be generated in the model to account for other plausible trends in the international demand for AR soybean products.

In the second case, assumptions should be made concerning the policy framework affecting the biodiesel supply chain. Scenarios of the policy framework can be developed considering the plausible evolution of government policies over time[30]. In this modelling framework, government policies include, among others, *ad-valorem* DETs and specific policies of the domestic biodiesel sector, such as the blending target, the biodiesel domestic supply quota and the biodiesel *cost-plus* pricing policy. Policy instruments are introduced as exogenous constants. However, different levels for each policy can be simulated to determine the supply response of the AR firm.

4.3. Intermediate and final demand for AR soybean products

4.3.1. Soybean producer demand

The soybean producer demand side accounts for two distinct demand drivers[31]:

- Soybean exports to the international market
- Soybean domestic crush for conversion into soybean oil and meal

The total soybean demand function faced by the AR soybean producer is the sum of the international demand for AR soybeans ($q_{soy}{}^{c}$) and the domestic demand by crushers ($q_{soy}{}^{cr}$).

The international demand for AR soybeans faced by the AR soybean producer can be denoted as:

$$q_{soy}{}^{c} = l_{soy}{}^{c} \times d_{soy}{}^{c} \times (P_{soy})^{e_{soy}{}^{c}} \qquad \text{Eq. 4-7}$$

where P_{soy} is the soybean international (export) price and $d_{soy}{}^{c}$ is the exogenous demand shifter. $e_{soy}{}^{c}$ and $l_{soy}{}^{c}$ are parameters representing the demand elasticity and the initial demand for AR soybeans in the international market.

The demand shifter $d_{soy}{}^{c}$ is assumed to account for the trend evolution of the demand for AR soybean exports. This trend account for the evolution of price of substitutes (rapeseed, palm), income, population, crushing capacity in importing countries and soybean production capacity in other producing countries.

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[30] In the simulation experiments, however, a single policy framework is specified and then different cases are tested to assess the influence of policy instruments ceteris paribus, i.e. all other things being equal or held constant.

[31] Soybean use as feed/food in the domestic market is assumed zero given the low share of soybean demand for feed/food in the Argentinean domestic market.

The demand of domestic soybean for crush, on the other hand, is given by the derived demand for soybean oil and meal. The domestic demand for soybean crush is endogenously modeled in the crusher supply model (section 4.4.2).

4.3.2. Soybean crusher demand

The soybean crusher demand side includes domestic and export demand for soybean oil and meal. Demand for soybean meal is assumed to be driven only by the demand level in the international market, given the low consumption of soybean meal in the domestic market (FAPRI 2010b). Soybean oil, on the other hand, has two destination markets[32]:

- Soybean oil exports to the international market
- Soybean oil domestic use for biodiesel production

The reduced form equation of the total demand function for soybean oil can then be expressed as a function of the international demand for AR soybean oil ($q_{oil}{}^{c}$) and the domestic demand for soybean oil by biodiesel producers ($q_{oil}{}^{bio}$).

The export demand for soybean oil faced by the Argentinean soybean crusher is denoted as:

$$q_{oil}{}^{c} = \lambda_{oil}{}^{c} \cdot \delta_{oil}{}^{c} \cdot (P_{oil})^{\varepsilon_{oil}{}^{c}} \qquad \text{Eq. 4-8}$$

where P_{oil} is the price of soybean oil in the international market and $\delta_{oil}{}^{c}$ is the exogenous demand shifter. Similarly, $\varepsilon_{oil}{}^{c}$ and $\lambda_{oil}{}^{c}$ represent the demand elasticity and the initial demand for AR soybean oil in the international market. The demand shifter accounts for structural changes in the price of substitutes (rapeseed oil, palm oil), income, population, government policies, crushing capacity in importing and other exporting countries and consumption patterns in other vegetable oil producing countries.

On the other hand, the demand of soybean oil for conversion into biodiesel is given by the derived demand for biodiesel in the domestic and international markets, so that the demand function of soybean oil for the domestic market is given by:

$$q_{oil}{}^{bio} = q(q_{bio}{}^{c}, q_{bio}{}^{dom}) \qquad \text{Eq. 4-9}$$

where $q_{bio}{}^{c}$ and $q_{bio}{}^{dom}$ are the international and domestic demand for biodiesel. The domestic demand of soybean oil for conversion into biodiesel is endogenously modeled in the biodiesel supply model (section 4.4.3).

The demand for AR soybean meal faced by the aggregated AR crusher is given by:

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[32] Domestic soybean oil use for food/feed is assumed to have no effect on the crusher production margin, as soybean oil demand in Argentina is not significant (only 2% of total soybean oil production), as Argentineans prefer sunflower over soybean oil.

$$q_{meal}{}^{c} = l_{meal}{}^{c} \times d_{meal}{}^{c} \times (P_{meal})^{e_{meal}{}^{c}}$$ Eq. 4-10

where P_{meal} is the price of soybean meal in the international market and $d_{meal}{}^{c}$ is the exogenous demand shifter. The shifter accounts for the evolution trend of structural factors such as those affecting AR soybean oil demand in the international market. However, provided that soybean oil and meal demands are driven by different factors, $d_{oil}{}^{c}$ and $d_{meal}{}^{c}$ represent different trends in the demand for each AR product.

A particular issue influencing the derived demand for exports of soybean product is the correlation between demand and prices of soybean and value-added products in the international market. For instance, if crushing capacity in importing countries increase and local soybean supply in those countries is constrained, this may increase soybean export demand and decrease soybean oil and meal export demand. Consequently, international prices of soybean products may change due to these demand shifts. Houck *et al.* (1972a) for instance, analysed price correlation between soybean and soybean products based on statistics of international prices time series. They found that soybean and soybean meal prices are more strongly correlated than soybean and soybean oil prices given the higher value share of meal in soybean crush. Soybean meal price is mainly linked to the price of other meal substitutes and analogously, soybean oil prices mainly adjust to prices of other vegetable oils. Soybean oil and soybean meal prices are almost independent, given the different drivers underpinning demand for each soybean product. Parameters $d_{soy}{}^{c}$, $d_{oil}{}^{c}$ and $d_{meal}{}^{c}$ then, are assumed to account for these correlations shifting demand and prices for soybean, soybean oil and meal.

4.3.3. Biodiesel producer demand

Argentinean biodiesel is produced both for the domestic and the international market. Each destination market has particular characteristics, provided that different government policies applied to each market. The biodiesel producer demand side therefore includes both demand drivers:

- Biodiesel domestic use to fulfil the domestic blending mandate
- Biodiesel export, mainly to fulfil the EU blending mandate

Biodiesel is assumed to be sold to the blender in the domestic market and to the final consumer in the international market. The reduced form of the demand function of AR biodiesel for export ($q_{bio}{}^{c}$) is given by:

$$q_{bio}{}^{c} = l_{bio}{}^{c} \times d_{bio}{}^{c} \times (P_{bio})^{e_{bio}{}^{c}}$$ Eq. 4-11

where P_{bio} is the price of biodiesel in the international market and $d_{bio}{}^{c}$ the AR demand shifters introduced exogenously in the model. For each year, the value of the demand shifter depends on assumption made about biodiesel blending target levels, other policies such as taxes and subsidies and the production capacity in biodiesel importing and exporting countries.

Domestic biodiesel demand, on the other hand, is primarily determined by the domestic blending target, so that the domestic biodiesel demand function is given by:

$$q_{bio}^{bl} = \alpha_{bio}^{gov} \cdot q_{fuel}^{c} \qquad \text{Eq. 4-12}$$

where q_{fuel}^{c} is the quantity of fuel demanded by the domestic fuel consumer and α_{bio}^{gov} is the blending target set by the government.

While the blending target fixes the share of biodiesel on fuel supply, domestic fuel demand depends on the price of the blended fuel (P_{fuel}^{c}) and a demand shifter (δ_{fuel}^{c}). Additional parameters represent initial conditions and the elasticity for the domestic fuel demand. The final domestic fuel demand is therefore given by:

$$q_{fuel}^{c} = \lambda_{fuel}^{c} \cdot \delta_{fuel}^{c} \cdot (P_{fuel}^{c})^{\varepsilon_{fuel}^{c}} \qquad \text{Eq. 4-13}$$

The demand shifter is assumed to account for other drivers of fuel demand such as the diffusion of cars and the evolution of passengers' mobility and is exogenously introduced in the model. The price of the blended fuel, on the other side, is assumed to change proportionally with the blending target.

Additional pricing policy instruments regulate the domestic fuel market including an import tariff on fossil diesel and a price cap for fuel consumers. The price cap policy constrains fuel consumer price so that the price of the blended fuel should not be higher than the price set by the government for the fuel blend. The pricing formulation for the blended fuel is therefore given by:

$$P_{fuel}^{c} = \alpha_{bio}^{gov} \cdot P_{bio}^{dom} + (1 - \alpha_{bio}^{gov}) \cdot P_{diesel}^{imp} (1 - \omega_{diesel}) \qquad \text{Eq. 4-14}$$

$$\text{s.t. } P_{fuel}^{c} \le P_{fuel}^{gov} \qquad \text{Eq. 4-15}$$

In Eq. 4-14, P_{bio}^{dom} and P_{diesel}^{imp} are the blender prices for biodiesel and fossil diesel, respectively and P_{fuel}^{gov} in Eq. 4-15 is the price cap for the blended fuel in the domestic market. The price of the fossil diesel to the blender depend on the diesel import price (P_{diesel}^{imp}) and the import tariff (ω_{diesel}) applied by the government.

The *cost-plus* biodiesel pricing policy set the biodiesel price for the domestic market, so that $P_{bio}^{dom} = P_{bio}^{gov}$, where P_{bio}^{gov} is the domestic biodiesel price set by the government.

4.4. Producers supply of AR soybean products

4.4.1. Soybean producer supply

A single input production function is assumed for the soybean producer, where the only variable input is land. The soybean supply function is therefore given by:

$$q_{soy}^{sp} = q_{land}^{sp} \cdot Y_{soy}^{sp} \qquad \text{Eq. 4-16}$$

where q_{land}^{sp} is the quantity of land allocated to soybean and Y_{soy}^{sp} is the soybean yield.

A special feature in modeling soybean production is the producer decision on the quantity of land to allocate to soybeans. Consequently, the soybean land supply function accounts for the relative net return per unit of land among competing land-uses. Hence, the reduced form equation of the land supply function for soybeans is given by

$$q_{land}^{sp} = q(g_{soy}^{sp}, g_{cc}^{cc}),$$

where g_{soy}^{sp} and g_{cc}^{cc} are the land unit profit (net return per unit of land) for soybean and an alternative competing crop, respectively.

The soybean land unit profit is estimated based on the soybean producer price, the average soybean yield, and the non-land soybean production costs as follows:

$$g_{soy}^{sp} = P_{soy} \cdot Y_{soy}^{sp} - C_{soy}^{sp} \qquad \text{Eq. 4-17}$$

The soybean producer price is defined as the soybean price in the international market minus the soybean export tax, given by expression:

$$P_{soy}^{sp} = P_{soy} \cdot (1 - w_{soy}) \qquad \text{Eq. 4-18}$$

where w_{soy} is the soybean export tax.

The national average soybean yield varies depending on the land productivity and the applied soybean cultivation method in each location. The modeling framework then accounts for regional specificities in soybean production. For this purpose, land available for soybean production at the national level is disaggregated in four regions as follows: north-west (*nw*) north-east (*ne*), central (*ce*) and south-east (s*e*). Hence, the average national soybean yield is estimated as a weighted sum of the soybean yield in each region given by:

$$Y_{soy}^{sp} = \sum_{sr} a_{sr}^{sp} \cdot Y_{sr}^{sp} \qquad \text{Eq. 4-19}$$

where α_{sr}^{sp} is the share of soybean supply by each region and Y_{sr}^{sp} is the average soybean yield in each region. The index *sr* denote the soybean supply region, so that $sr = \mathrm{nw}, \mathrm{ne}, \mathrm{c}, \mathrm{se}$. The share of each region on soybean supply is modeled as an exogenous variable and is assumed constant.

In each region, different soybean cultivation methods are applied. For modeling purposes, soybeans are assumed to be produced through three different cultivation methods *m*, namely: first occupation no tillage (*font*), first occupation conventional tillage (*foct*) and second occupation no tillage (*sont*). Each cultivation method is associated with an average soybean yield that depends on the inputs applied in each method and the average regional productivity of land.

The regional average soybean yield therefore is modeled based on a land productivity index specific for each region (p_{sr}), the average yield obtained from each cultivation method ($Y_{sr,m}^{sp}$) and the share of soybean cultivation methods in each region ($\alpha_{sr,m}^{sp}$). So, for each region, the regional average soybean yield is given by:

$$Y_{sr}^{sp} = p_{sr} \cdot \sum_{m} \alpha_{sr,m}^{sp} \cdot Y_{sr,m}^{sp} \qquad \text{Eq. 4-20}$$

The index *m* denotes the soybean cultivation method so that $m = \mathrm{font}, \mathrm{foct}, \mathrm{sont}$. Cultivation methods shares are assumed specific for each region, constant and exogenous[33].

The cultivation method *m* determines the quantity of non-land inputs *i* applied per hectare of soybean ($q_{i,m}^{sp}$). Non-land production inputs account for pesticides, fertilisers, machine labour, transport and seed use for each cultivation method. Non-land soybean production cost for each method *m* ($C_{soy,m}^{sp}$) is then calculated as the sum product of the price and the quantity of each individual input *i*. The regional soybean production cost per unit of land is then estimated based on the share of cultivation method *m* in each region *sr*, as:

$$C_{soy,sr}^{sp} = \sum_{m} \alpha_{soy,m}^{sp} \cdot C_{soy,m}^{sp} = \sum_{m} \left(\alpha_{soy,m}^{sp} \cdot \sum_{i} P_{i}^{sp} \cdot q_{i,m}^{sp} \right) \qquad \text{Eq. 4-21}$$

where P_i^{sp} is the price of each non-land input *i* to the soybean producer *sp*.

The national average cost per unit of land for soybean cultivation is then modeled as the weighted average of the regional soybean production cost. To this end, Eq. 4-21 is affected by the share of soybean supply regions ($\alpha_{soy,sr}^{sp}$), similarly to the estimation of the average soybean yield. Then, based on equations Eq. 4-18, Eq. 4-19 and Eq. 4-21 the soybean land unit profit is estimated.

Finally, the quantity of soybean exports is given by the quantity of soybean produced and the quantity diverted to domestic crush for soybean oil and meal production, so that,

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[33] At present, 75% of soybean production is done under no-tillage practices.

$$q_{soy}{}^{\exp} = q_{soy}{}^{sp} - q_{soy}{}^{cr} \qquad \text{Eq. 4-22}$$

where $q_{soy}{}^{cr}$ is the quantity of soybean supplied to the crusher.

4.4.2. Soybean crusher supply

The supply side of the crusher model accounts for the production of soybean oil and meal and their allocation to the domestic and international markets. Soybean oil and meal are assumed joint-products from soybean crushing with fix proportion in output. Given the assumed fixed proportion, the quantity of soybean oil and meal produced, denoted as $q_{oil}{}^{cr}$ and $q_{meal}{}^{cr}$, respectively, can be expressed as a function of soybean crushed, so that soybean oil and meal production is given by:

$$q_{oil}{}^{cr} = q_{soy}{}^{cr} \times Y_{oil}{}^{cr} \qquad \text{Eq. 4-23}$$

$$q_{meal}{}^{cr} = q_{soy}{}^{cr} \times Y_{meal}{}^{cr} \qquad \text{Eq. 4-24}$$

where $Y_{oil}{}^{cr}$ and $Y_{meal}{}^{cr}$ are the constant conversion yields of soybean into soybean oil and meal, respectively.

As Meyers and Helmar (1991) have reported, soybean crush is modeled as a constant elasticity function that depends on the gross soybean processing margin. The gross soybean processing margin (the gross return per tone of soybeans processed) is the main decision variable that crushers use in deciding when to process soybeans. This crush margin represents the added value of meal and oil produced from processing a ton of soybeans. The soybean crush function can then be expressed as:

$$q_{soy}{}^{cr} = \lambda_{soy}{}^{cr} \times \left(\gamma^{cr}\right)^{\varepsilon_{cr}} \qquad \text{Eq. 4-25}$$

In Eq. 4-25, $\lambda_{soy}{}^{cr}$ and ε_{cr} are parameters representing the initial condition and the elasticity of soybean processing to the crush margin, respectively.

The soybean crush margin is expressed based on the weighted price of soybean oil and meal, minus the price of soybean (Meyers *et al.* 1991). The soybean crush margin, denoted as γ^{cr}, is therefore given by the following expression:

$$\gamma^{cr} = P_{oil}{}^{cr} \times Y_{oil}{}^{cr} + P_{meal}{}^{cr} \times Y_{meal}{}^{cr} - P_{soy}{}^{cr} \qquad \text{Eq. 4-26}$$

The crush margin represents the supply relation for soybean crush as derived in Appendix 9.1.2. The weighted price is the sum of the products of soybean oil and meal and their respective conversion yields. Conversion yields are complementary, so that they sum one.

Soybean oil exports are modeled based on the quantity of soybean oil produced and the quantity supplied to biodiesel production by both firms *f*, so that,

$$q_{oil}^{\exp} = q_{oil}^{cr} - \sum_{f} q_{oil}^{f} \qquad \text{Eq. 4-27}$$

where q_{oil}^{f} is the quantity of oil supplied to each biodiesel producer . The index *f* denotes the biodiesel producer type, so that *f=s&m,lg*.

In the case of soybean meal, the model assumes all soybean meal production is exported, so that,

$$q_{meal}^{\exp} = q_{meal}^{cr} \qquad \text{Eq. 4-28}$$

4.4.3. Biodiesel producer supply

The supply side of the biodiesel producer model accounts for biodiesel production by each producer type and its allocation to the domestic and international markets.

The quantity of biodiesel produced is given by the supply of soybean oil to each biodiesel producer and the biodiesel conversion yield. Considering that biodiesel producers are disaggregated in *s&m* and *lg* firms, a specific supply function is defined for each producer type *f*., given by expression:

$$q_{bio}^{f} = q_{oil}^{f} \cdot Y_{bio}^{f} \qquad \text{Eq. 4-29}$$

where Y_{bio}^{f} is the respective conversion yield of each biodiesel producer.

Oil supply for biodiesel production is modeled as a constant elasticity function depending on the unit profit (net average return to capital) of the biodiesel producer. While soybean oil transesterification yields two outputs (biodiesel and glycerine), glycerine is an inexpensive by-product acting in a small domestic market with a low price relative to biodiesel[34]. The unit profit of each biodiesel producer type is therefore assumed to depend only on the biodiesel producer price. To this end, provided that biodiesel production costs and government policies are given, each supply function can be calibrated based on the international and domestic biodiesel prices.

For each biodiesel producer type (*f*), the soybean oil supply function is given by:

$$q_{oil}^{bio} = \lambda_{oil}^{bio} \cdot (\gamma_{bio}^{f})^{\varepsilon_f} \qquad \text{Eq. 4-30}$$

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[34] Glycerine is mainly domestically used in Argentina and production is not significant. Glycerine price was 100 US$/t in 2005 in the domestic market, compared with 833 US$/t for biodiesel in the US market. Therefore, glycerine production from soybean-oil transesterification is not included as is it assumed that glycerine demand has a marginal effect on the biodiesel production margin.

In Eq. 4-30, g_{bio}^{f} is the weighted unit profit (transesterification margin) of the biodiesel producer and l_{bio}^{f} and e_{bp} are parameters incorporating the initial condition and the elasticity of oil supply with respect to the producer margin.

Concerning the biodiesel producer unit profit, provided that production costs are assumed to be the same independently of the biodiesel market destination, g_{bio}^{bp} can be expressed based on the biodiesel producer price in each market, the share of production diverted to each market and the unit production cost. For each producer then, the weighted biodiesel unit profit is defined as:

$$g_{bio}^{bp-f} = b_{bio}^{\mathrm{exp}} \times P_{bio}^{\mathrm{exp}} + b_{bio}^{bl} \times P_{bio}^{gov} - C_{bio}^{bp} \qquad \text{Eq. 4-31}$$

where b_{bio}^{exp} and b_{bio}^{bl} are the share of biodiesel supplied to the international and the domestic market, respectively and C_{bio}^{bp} is the unit production cost.

Different price formulations apply to biodiesel supply to the international and domestic markets. In the first case, the biodiesel producer price for export (P_{bio}^{exp}) is determined by the biodiesel international price (P_{bio}), the biodiesel export tax (w_{bio}) and additional taxes (x_{bio})[35] applied to biodiesel producers focused on the international market. Hence, the biodiesel producer price formulation for the international market is given by:

$$P_{bio}^{\mathrm{exp}} = P_{bio} \times (1 - w_{bio} - x_{bio}) \qquad \text{Eq. 4-32}$$

On the other hand, the domestic biodiesel price is set by the government. In the Secretariat of Energy's Resolution 554/2010 (SE 2010b), the government agreed with several biodiesel producers to supply the required biodiesel quantity to fulfil the B7 domestic biodiesel blending target. The agreement is implemented as a contract in the form of a *fixed fee cost-plus* contract (CPFF)[36]. In this type of contract, the product price is formulated based on the *cost-plus* pricing method. Basically, this approach sets prices that cover the cost of production and provide enough profit margin to the firm to earn its target rate of return (Petersen *et al.* 2006). The main purpose of this price formulation is to provide *s&m* firms an incentive to enter the market and to actually exist. The government then aims to provide *s&m* firms an "abnormal" rent that motivates them to produce biodiesel for the domestic market.

As reported by the SE (2010b), the biodiesel *cost-plus* domestic price (P_{bio}^{gov}) is modeled based on the soybean oil producer price (P_{oil}^{bp}), plus the *mark-up* unit profit (g_{bio}^{bp-gov}).The price set by the government is estimated based on the cost structure of the aggregated *s&m* biodiesel producer. Soybean oil represents the main component of biodiesel production costs. Therefore additional costs, such as the methanol price and other costs are assumed constant. The domestic biodiesel price formulation is given by:

$$P_{bio}^{gov} = C_{bio}^{bp}(P_{oil}^{bp}) + g_{bio}^{bp-gov} \qquad \text{Eq. 4-33}$$

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[35] Biodiesel supplied the domestic market is exempted of these additional taxes.

[36] Also termed Cost Reimbursement Contract (CRC)

The soybean oil price to the biodiesel producer (P_{oil}^{bp}) in equation Eq. 4-33, varies among biodiesel producer types. Following research undertaken by Joskow (2006), due to vertical integration transaction and transport costs for soybean oil are assumed lower for the large biodiesel producer than for the S&M biodiesel producer. Total and average biodiesel production costs therefore are assumed lower for the large biodiesel producer. Moreover, biodiesel conversion efficiency is assumed higher for the large firm than for the *s&m* firm due to the assumed higher performance of large firms.

In both cases, however, oil conversion into biodiesel is assumed to be done through transesterification with methanol, a mature technology in biodiesel production and so, the oil conversion yield for each producer type is assumed constant. P_{oil}^{bp} is modeled as a function of the soybean oil price in the international market, the transaction costs (C_{oil}^{tr}), the transport costs (C_{oil}^{tp}), and the export tax (w_{oil}), so that:

$$P_{oil}^{bp} = P_{oil} \cdot (1 + C_{oil}^{tr} + C_{oil}^{tp} - w_{oil}) \qquad \text{Eq. 4-34}$$

In the case of Argentina, two constraints regulate biodiesel market destinations. In the first case, biodiesel supply to the domestic market is regulated by the biodiesel supply quota (SE 2010a). In the second case, biodiesel supply to the international market is regulated by the GHG emission saving threshold (EC 2009).

The quantity of biodiesel supplied by each firm to the domestic market is regulated through supply quotas based on the firm size (SE 2010b). Consequently there is no competition among biodiesel producers. The government reserves the domestic market mainly to *s&m* firms (SyCDNA 2006). Large producers, on the other hand, can sell in the domestic market only when production from *s&m* firms is not enough to achieve the blending target level.

Provided that the model assumes two types of aggregated biodiesel producers, the supply quota is modeled as a share of biodiesel domestic supply assigned to the aggregated *s&m* firm. Therefore, the quantity of biodiesel supplied by the aggregated *s&m* firm to the domestic market is given by:

$$q_{bio}^{s\&m-bl} = \alpha_{bio}^{s\&m} \cdot q_{bio}^{bl} \qquad \text{Eq. 4-35}$$

$$\text{s.t. } \alpha_{bio}^{s\&m} \cdot q_{bio}^{bl} \le q_{bio}^{s\&m} \qquad \text{Eq. 4-36}$$

where $\alpha_{bio}^{s\&m}$ is the supply quota assigned to the aggregated *s&m* firm, q_{bio}^{bl} the domestic biodiesel demand and $q_{bio}^{s\&m}$ is the quantity of biodiesel the *s&m* firm is willing to produce given its aggregated unit profit level (Eq. 4-30).

On the other hand, the quantity of biodiesel supplied by the aggregated large firm to the domestic market is modeled as the domestic biodiesel demand minus the supply of the aggregated *s&m* firm, so that:

$$q_{bio}^{\lg - bl} = q_{bio}^{bl} - q_{bio}^{s\&m - bl} \qquad \text{Eq. 4-37}$$

In the case of the international market, where biodiesel is mainly exported to the EU, an additional constraint is the GES threshold for the biodiesel. The GES ($er_{bio,sr}$) of the biofuel depends mainly on production patterns in soybean supply. Soybean production patterns include the share of soybean cultivation methods and the share of unmanaged lands on managed land expansion. Consequently, different er_b are associated with each soybean supply region.

The quantity of biodiesel exported by each producer type ($q_{bio}^{f-\exp}$) is therefore given by the quantity of biodiesel produced by each producer type minus the quantity allocated to the domestic biodiesel market, subjected to the fulfilment of the EU-RED GES threshold as follows:

$$q_{bio}^{f-\exp} = q_{bio}^{f} - q_{bio}^{f-bl} \qquad \text{Eq. 4-38}$$

$$\text{s.t. } er_{bio,sr} \geq er_{bio}^{imp} \qquad \text{Eq. 4-39}$$

where q_{bio}^{f-bl} is the quantity of biodiesel supplied to the aggregated blender (*bl*) in the domestic market and er_{bio}^{imp} the GES threshold for the biodiesel imposed by the EU-RED.

4.5. Land-use change modeling

Land-use change modeling is performed as follows. Firstly, the availability of suitable land for agricultural uses is defined. A land structure is defined, based on the disaggregation of suitable available agricultural land in hierarchical levels. Based on this land structure, an allocation procedure is defined to distribute land among competing agricultural land-uses. In a second step, the approach to model land supply for agricultural uses is defined based on the possibility to expand agricultural (managed) land into unmanaged lands. Finally, the approach to estimate land-use changes from soybean production and its allocation to biodiesel is described, incorporating the additional drivers of soybean production.

Land-use change modeling is based on the following basic assumptions:

- Total suitable agricultural is fixed for each managed land-use type.
- Managed land is a mobile and heterogeneous production factor.
- Cropland and managed land allocation depends on relative net returns per unit of land (unit profit) between competing managed land-uses.
- Managed land supply for each managed land-use type depends on the aggregated land unit profit.

- Managed land expansion is allocated between unmanaged land-uses based on constant exogenous shares for each unmanaged land-use type in each soybean supply region.
- Land-use changes are allocated to biodiesel based on the share of soybean for biodiesel on soybean land supply.

4.5.1. Total suitable agricultural land and land productivity

Land is a primary production factor and probably the most important one in the production function of agricultural products. Total suitable agricultural land ($q_{land}{}^{T}$) is defined as the quantity of land at the country level that can hold agricultural land-uses with a minimum productivity level (Eq. 4-40).

$$q_{land}{}^{T} = \sum_{x}^{X} L_x(\mu_x) \qquad \text{s.t.} \qquad \mu_x \geq \bar{\mu} \qquad \text{Eq. 4-40}$$

The approach used by van Meijl *et al.* (2006) is followed to estimate total suitable agricultural land for each managed land-use type. The advantage of this approach is that land suitability is estimated based on geo-referenced land productivity data. Consequently, the estimation of land suitable to hold agricultural land-uses accounts for biophysical constraints limiting the expansion possibilities of agricultural land.

Total suitable agricultural land is determined by dividing the national territory in equal square parcels (L_x). Each parcel x has a land productivity index μ_x which indicates the percentage difference between the parcel yield and the maximum obtainable yield at the country level. The suitability threshold $\bar{\mu}$ defines the maximal acceptable percentage difference between yields and represents the minimum acceptable productivity level.

The parcel productivity is calculated based on the aggregated productivity of a set of selected land-uses. Parcels are sorted by decreasing productivity, so that the land productivity index of the last parcel added to $q_{land}{}^{T}$ equals the maximum threshold.

Total suitable agricultural land depends on the productivity of land. The minimum productivity threshold however differs among managed land-use types. Indeed, higher productivities are generally required to obtain acceptable returns to cropland than to pastureland. In order to account for this effect, total suitable agricultural land for each managed land-use type is estimated based on specific land productivity curve (Figure 4-3).

Land productivity curves take the exponential form and depend on the maximum land suitability potential ($q_{land}{}^{crop-suit}$, $q_{land}{}^{past-suit}$) and the land productivity index. The quantity of land suitable for cropland is lower than the quantity of land suitable for pasture (INDEC 2002). Consequently, it is assumed that less land is available for cropland than for pasture. This implies that land productivity decreases more smoothly for pastureland than for cropland, given the shape of the respective curves.

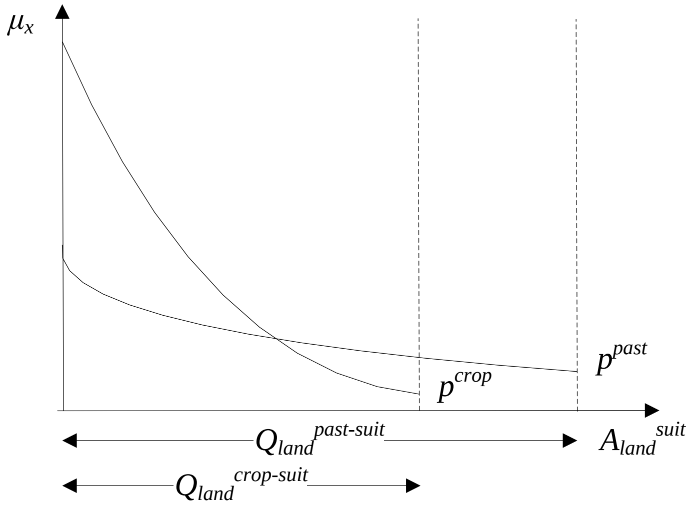

Figure 4-3. Land productivity curve by managed land type.

4.5.2. Land structure

Land is modeled assuming a hierarchical structure consisting in different levels. As studies by Conforti and Londero (2001) and Golub *et al.* (2006) have reported, land is disaggregated to account for heterogeneity and imperfect mobility of land among a set of selected land-uses. Land heterogeneity is assumed to derive from different land productivities among land-uses (Baltzer and Kløverpris 2008). Imperfect land mobility is assumed to derive among other factors, from differences in costs of land conversion, managerial inertia and un-measured benefits from crop rotation (Golub *et al.* 2006).

This conventional approach is adopted by assuming 12 final land-uses, aggregated in a three-level nesting structure (Figure 4-4). Each level aggregates the quantity of land available in each final land-use type, as follows:

- Crop (*n*): Land occupied with a specific crop. Includes soybean and corn land, with n=*soy, corn.*
- Managed land (l): Land under economic use. Aggregates cropland and pasture land, with l=*crop, past.*
- Unmanaged land (k): Land not under economic use (nature land). Aggregates forest, grassland, mixedland, savannas, shrubland and degraded land, with k=*for, grass, mix, sav, shrub, deg.*

Suitable land for cropland can generally hold a large variety of crops. In the Argentinean case 60% of cropland is occupied by soybean and corn, accounting also for the two main competing crops (INDEC 2002). Therefore, in the first level, cropland is represented by two competing crops *n*, namely soybean (*soy*) and corn (*corn*).

Managed lands typically account for cropland, pastureland and managed forests (Taheripour *et al.* 2008). In Argentina, cattle production is done partly on cropland and partly on unmanaged natural land (INDEC 2002). So, a fraction of grasslands and savannas is allocated to pastureland for cattle production[37]. For simplicity, managed forest land is assumed to be natural forestland, as it only accounts for 3% of total forest land (INDEC 2002). In the second level therefore, cropland (*crop*) and pasture (*past*) uses are aggregated into managed land, where each managed land type is denoted as *l*.

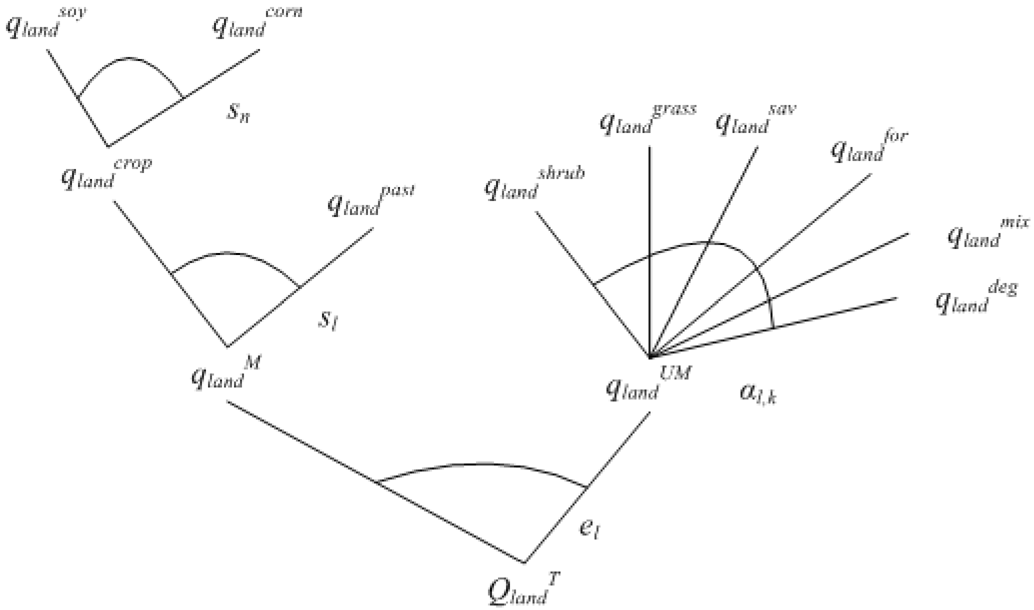

Figure 4-4. Land supply structure.

Finally, in the third level, managed and unmanaged lands are aggregated into the total available suitable agricultural land. This level defines the total suitable agricultural land to allocate managed land-uses, and consequently the possibility of expansion of managed into unmanaged land.

Unmanaged land is aggregated in a single nesting structure, summing up the total quantity of available unmanaged land. The unmanaged land nesting structure includes several unmanaged land-use types, denoted as *k*. Following the ICF model (ICF 2009), six different unmanaged land-uses are assumed, including forest (*for*), grassland (*grass*), mixed land (*mix*), savannas (*sav*), shrubland (*shrub*) and degraded land (*deg*).

4.5.3. Managed land allocation

An allocation procedure is then defined to distribute land among competing land-uses in the same hierarchical level. Land allocation among competing managed land-uses is modeled based on a modified version of the constant elasticity of transformation (CET) function, to account for physical units in land conversions. Physical units are required to estimate GHG emissions from LUC. The CET function accounts for imperfect mobility among competing land-uses.

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[37] Cattle rising are done on natural grasslands. Cattle breeding is partially done on managed pastures (cropland) and dairy farms are located in croplands Rearte, D. (2007). Distribucion territorial de la ganaderia vacuna. Programa National de Carnes, . Balcarce, BA, Argentina, Estación Experimental Agropecuaria Balcarce - Instituto Nacional de Tecnología Agropecuaria (INTA) 12.For simplicity, a single use for pastureland as cattle rising for beef production is assumed.

The CET function is specified as a three-level nesting structure, following land disaggregation in Figure 4-4. Denoting σ_n and σ_l as the elasticity of transformation for competing crops and managed lands, respectively, the nested CET function respects that $\sigma_n \geq \sigma_l$, based on the assumption that rationally it is easier to convert land among crops than among cropland and pasture, and similarly, among managed lands than among managed and unmanaged lands.

In the first level, the CET function allocates land between crop types based on the net return to soybean (n_1) respect to corn (n_2) per unit land. (γ_{land}^{n}). The land allocation function for soybean land is then given by:

$$q_{land}^{sp} = \lambda_{land}^{sp} \cdot \left(\frac{\gamma_{land}^{n1}}{\gamma_{land}^{n2}} \right)^{\sigma_n} \qquad \text{Eq. 4-41}$$

$$\text{s.t. } \sum_{n} q_{land}^{n} = q_{land}^{l} \qquad \text{Eq. 4-42}$$

where σ_n is the elasticity of transformation between competing crop *n1* and *n2* and λ_{land}^{sp} a parameter representing the initial quantity of soybean land at the national level. In order to account for biophysical limits in land availability, the land allocation function for competing crops respects that the total land allocated among crops should equal the total land available under cropland. Therefore a constraint is added in Eq. 4-42 to land supply for soybean production.

Analogously, land conversion among managed lands is modeled as a CET function depending on relative land unit profits so that $q_{land}^{l1} = q\left(\lambda_{land}^{l1}, \gamma_{land}^{l1}, \gamma_{land}^{l2}, \sigma_l\right)$, where γ_{land}^{l1} is the aggregated cropland unit profit and γ_{land}^{l2} is the pastureland unit profit. Initial conditions and the transformation elasticity between managed land-uses *l* are given by parameters λ_{land}^{l1} and σ_l, respectively. The elasticity parameter defines the easiness of conversion between cropland and pasture. Analogously to Eq. 4-42, this procedure considers that the sum of the quantity of land allocated to each managed land-use *l* should be equal to the total managed land, so that $\sum_{l} q_{land}^{l} = q_{land}^{M}$.

4.5.4. Managed land supply

The supply of land for managed land-uses depends on the possibility of expansion of the agricultural frontier. The modeling framework therefore allows for managed land to increase, representing the expansion possibility of cropland and pastures into natural land. Two major issues are being considered in modeling managed land supply, namely:

- The quantity of managed (agricultural) land that expands into unmanaged (natural) land.
- The type of converted unmanaged land-uses.

Land supply for each managed land-use type is modeled following (van der Mensbrugghe 2005). In this approach the quantity of managed land that expands into unmanaged land depends on the aggregated net return to each managed land-use type. Land unit profits of managed lands are used due to the absence of a land value for unmanaged lands and the lack of detailed geo-referenced data. A land supply function is then defined for cropland and pastureland depending on their own aggregated unit profit.

For each managed land-use type a constant elasticity function is specified (Eq. 4-43).Analogously to Eq. 4-42, this procedure considers that the sum of the quantity of land supplied to each managed land-use *l* should equal the total available agricultural land. Additionally the quantity of land supplied to each managed land-use *l* should be equal or lower than the maximum suitable available land for each managed land-use type (Eq. 4-44). Formally managed land supply for each managed land-use type is given by:

$$q_{land}{}^{l} = \lambda_{land}{}^{l} \cdot \left(g_{land}{}^{l}\right)^{e_l} \qquad \text{Eq. 4-43}$$

$$\text{s.t. } \sum_{l} q_{land}{}^{l} = q_{land}{}^{M}$$

$$q_{land}{}^{l} \leq q_{land}{}^{l-suit} \qquad \text{Eq. 4-44}$$

where $g_{land}{}^{l}$ is the aggregated unit profit of managed land *l* and $\lambda_{land}{}^{l}$ and e_l are parameters representing initial conditions and the land supply elasticity, respectively.

Different land supply elasticities (e_l) are assumed for cropland and pasture land supply given the different land productivity thresholds and other factors affecting land conversion decisions for each managed land-use type. Parameter e_l is a constant that was calibrated to fit historical land expansion patterns for cropland and pasture land in each region.

Cropland average unit profit is estimated as the weighted sum of soybean and corn land unit profits. Pastureland revenue depends on the beef price, the pasture land yield and the unit production costs. Soybean and corn revenues depend on the crop price, yield and unit production cost. Crops and pasture yield are partially determined by land productivity that in turn affects the expected land unit profit from cultivation in new lands. Considering that managed lands are assumed to expand into less productive lands, yields and consequently land revenues are assumed to decrease as managed lands increases.

Finally, the quantity of managed land that expands into unmanaged land is allocated among unmanaged land-use types following the approach used by Searchinger *et al.* (2008). This approach assumes future land-use changes will follow the same historical land-use conversion patterns. To this end, the shares of unmanaged land-uses on managed land expansion are exogenously introduced, considering historical trends in each soybean supply region.

4.5.5. Direct land-use change from soybean production for biodiesel

Direct land-use change (dLUC) from soybean production for biodiesel is estimated based on the following procedure. Firstly, the quantity of cropland expansion into managed and unmanaged lands is estimated. Then, dLUC from cropland expansion is allocated to soybean production for biodiesel.

For modeling purposes, soybean production is assumed to be located in four different supply regions *sr*. Land-use patterns in each region determine the share of unmanaged land-uses *k* on managed land-use *l* expansion ($\alpha_{l,k}^{sr}$). Therefore, for each region *sr*, the expansion rate of managed land *l* (cropland) into each unmanaged land-use *k* ($q_{l,k}$) depends on the quantity of land supplied to each managed land *l* and the historical share of land-use conversion from each managed land *l* into each unmanaged land *k*. Cropland (*l*) expansion into each unmanaged land-use *k* is then given by:

$$q_{l,k} = \alpha_{l,k}^{sr} \times q_{land}^{l} \qquad \text{Eq. 4-45}$$

A similar formulation is specified for pastureland expansion into unmanaged lands.

In this modeling framework, cropland and pasture compete for managed lands. In order to estimate dLUC from cropland expansion, the rate of cropland expansion into pasture land is specified. This rate depends on the supply of cropland (q_{land}^{l}) and the share of cropland on pasture expansion ($\alpha_{l,l}^{sr}$).

$$q_{l,l} = \alpha_{l,l}^{sr} \times q_{land}^{l} \qquad \text{Eq. 4-46}$$

In Eq. 4-46, $\alpha_{l,l}^{sr}$ is estimated based on the land supply CET function that allocates land between cropland and pasture.

Direct land-use change (dLUC) induced by cropland expansion is then estimated based on Eq. 4-46 and Eq. 4-47 as:

$$dluc_{l} = q_{l,l} + \sum_{k} q_{l,k} \qquad \text{Eq. 4-47}$$

In the Argentinean case, the soybean producer decision on the quantity of land diverted to soybean is independent of the market destination of the product. Moreover, there is no tradability system that allows identifying the location from where soybean for biodiesel is supplied. An allocation procedure is then proposed based on assigned dLUC from soybean expansion to the biodiesel.

The allocation of dLUC from soybean production to the biodiesel is then performed based on direct land-use estimated through Eq. 4-47, the shares of soybean in cropland supply (α_{soy}^{crop}) and the share of soybean for biodiesel on soybean production (α_{soy}^{bio}), so that,

$$dluc_{soy}^{bio} = dluc_{crop} \times \alpha_{soy}^{crop} \times \alpha_{soy}^{bio} \qquad \text{Eq. 4-48}$$

The share of soybean in cropland supply is given by the ratio between land supply for soybean production and the aggregated land supply for cropland: Similarly, the share of soybean for biodiesel on soybean production depends on the quantity of biodiesel production and the quantity of soybean production. This allocation procedure allows assigning land-use change GHG emissions to biodiesel; provided that other drivers, such as soybean, oil and meal international demand also underpin land supply for soybean production. The allocation of emissions to biodiesel exports is finally assigned based on the share of biodiesel production diverted to the export market (b_{bio}^{exp}).

4.6. GHG emissions modeling

4.6.1. GHG emission balance

GHG emissions from biodiesel production for each producer type are calculated based on the methodology of the EU-RED (EC 2009). In the EU-RED the GHG emission balance of the biofuel is estimated as the sum of all emissions from each individual process involved in the supply and use of the biofuel.

Specific emissions of individual processes account for emissions from extraction or cultivation of raw materials (*eec*), annualised emissions from carbon stock changes caused by land-use change (*el*), emissions from processing (*ep*), emissions from transport and distribution (*etd*) and emissions from the fuel use (*eu*). The simplified functional form is given by:

$$e_{bio,sr}^{bp} = eec^{m} + el_{sr} + ep + etd + eu \qquad \text{Eq. 4-49}$$

A specific treatment is given for emissions from cultivation of raw materials and annualised emissions from carbon stock changes caused by land-use change. On the other hand, constant emissions from the feedstock processing and conversion phases and constant emissions from transport, distribution and use are assumed. This choice relies on the fact that solvent extraction and transesterification are well established technologies with low potential for substantial improvements in the short to medium terms. A conventional approach is used to allocate emissions from industrial processes (crushing and transesterification) based on prices, conversion yields and energy value of co-products.

Finally, emission savings from soil carbon accumulation via improved agricultural management, from carbon capture and replacement and from excess electricity from cogeneration are assumed to be zero.

4.6.2. GHG emissions from soybean cultivation

Soybean cultivation emissions are specific to each cultivation method. For each method therefore, GHG emissions are estimated based on the quantity of inputs used per hectare, the soybean yield and input-specific emission factors as follows:

$$eec^{m} = \frac{\sum_{i}\left(q_{i.,m}^{sp} \times ef_{i}\right)}{Y_{soy}^{m}} \qquad \text{Eq. 4-50}$$

where ef_z is a constant emission factor for each input that accounts for CO_2eq emissions during the production and additional process needed to make the product/service available. Note that emission factors are assumed constant and input specific, so that they do not change over time or as a function of the cultivation method.

4.6.3. GHG emissions from direct land-use change

Land-use change emissions account for direct GHG emissions (dLUC) from carbon stock changes in soil and biomass resulting from soybean expansion into other managed and unmanaged land-uses. The estimation of dLUC GHG emissions is performed in two steps. Firstly, GHG emissions from dLUC are calculated based on the rate of cropland expansion into unmanaged (Eq. 4-45) and pasture land (Eq. 4-46) and individual emission factor for each land-use type, as follows:

Eq. 4-51

$$el_{sr} = \sum_{k} q_{l,k} \cdot ef_k + \sum_{l} q_{l,l} \cdot ef_l$$

Annualised emissions from carbon stock changes caused by land-use change are calculated by dividing total emissions equally over 20 years based on Annex V C-7 equation of the EU-RED. Emission factors account for carbon stock changes in soil and biomass of managed (*l*) and unmanaged land-uses (*k*). It is assumed that cropland carbon stock is unique to all crops. Consequently inter-crop land-use changes do not induce LUC GHG emissions. Emission factors per hectare (ef_k, ef_l) are annualised considering a fixed time horizon for land occupation (and consequently emissions amortisation), following the EU-RED (EC 2009).

dLUC GHG emissions from cropland expansion are then allocated to soybeans and finally to the biodiesel, considering the economic value share of each soybean product in each market, i.e. soybean for export, soybean oil exports, soybean meal exports and biodiesel for the domestic and export markets. The allocation procedure accounts for the mass and economic performance of the product. The quantities produced of each product depend on the respective price of the product. Formally, the allocation equation is similar to Eq. 4-48, based on the share of cropland on soybean land and the share of biodiesel on soybean production.

4.6.4. GHG emissions savings

The biofuel GES ($er_{bio,sr}$) is estimated by comparing biodiesel life cycle GHG emissions with those of the reference fossil diesel. The $er_{bio,sr}$ is calculated as the ratio between:

the difference between biodiesel and fossil diesel GHG emission

the fossil diesel GHG emission

The EU-RED formulation is given as follows:

Eq. 4-52

$$er_{bio,sr} = \frac{e_{bio,sr} - e_f}{e_f}$$

where e_f are the life cycle GHG emissions from fossil diesel production and use. Regional GES of the biodiesel are estimated based on the region from where the feedstock (soybean) is obtained.

5. Dynamic simulation model

5.1. Overview of the simulation approach

5.1.1. Architecture of the simulation model

The simulation approach aims to estimate the quantity of biodiesel exports (from both producer types) subjected to the condition that the biofuel GES, including dLUC from soybean production for biodiesel, should fulfil the GES threshold. Several simulation steps are required to achieve this result which involved the development of a simulation model.

Due to the complexity of the system being addressed, the simulation model is divided in modules with each one addressing a specific issue. Module integration and the inclusion of additional internal databases form a single model where simulation leads to the final result (Figure 5-1).

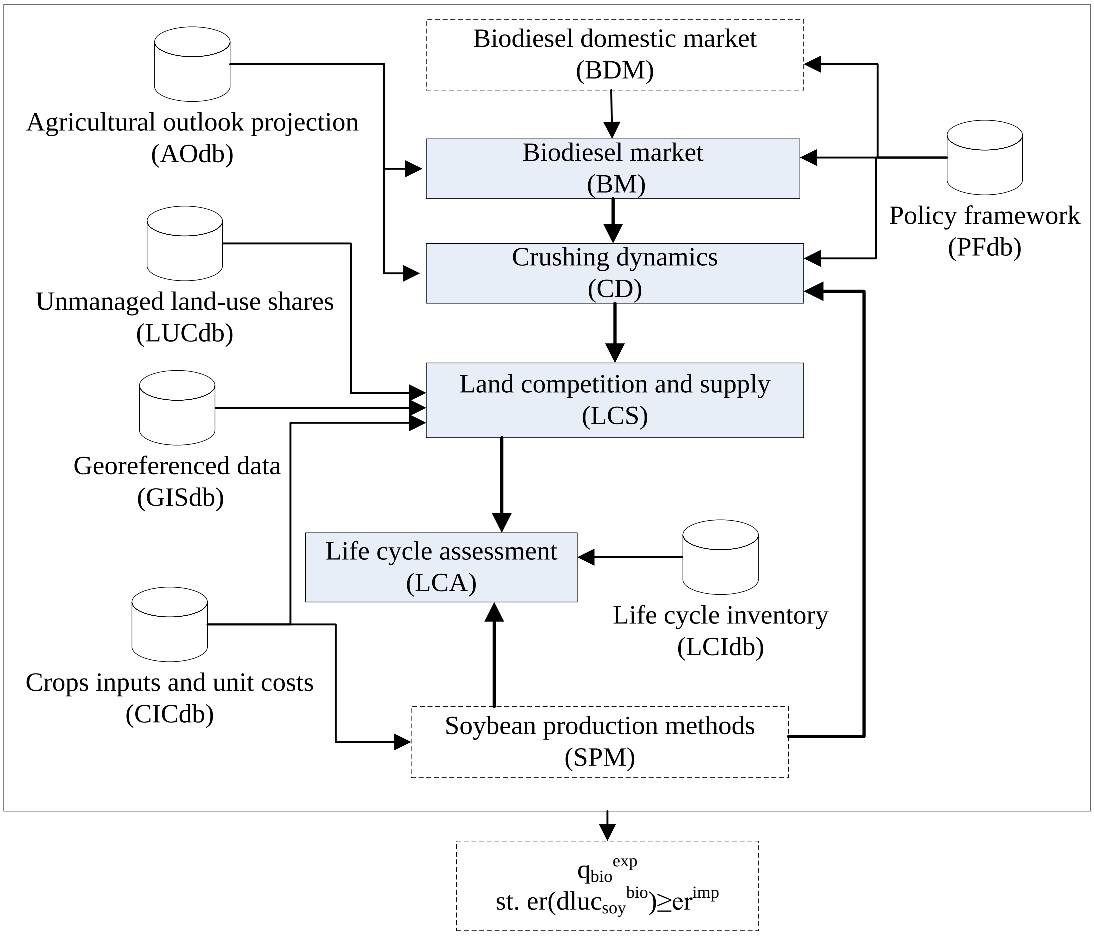

Figure 5-1. Model architecture.

The model architecture is divided in four main modules and two sub-modules that are linked between each other. Internal databases are used to stock input data and are implemented as

Excel® spreadsheets from where module parameters, projections and initial values are obtained

The **biodiesel market (BM)** module simulates biodiesel production by producer type and its allocation between biodiesel market destinations. The module gets input variables from the Agricultural Outlook (AOdb) and the policy framework (PFdb) database. A special sub-module (BDM) is linked to simulate domestic biodiesel demand.

The **crushing dynamics (CD)** module is an economic model that simulates supply responses in the soybean and value-added sectors. Input data is given by the AOdb and the PFdb databases and a special sub-module, the soybean production methods (SPM) module, is linked to simulate soybean production costs and yield.

The **land competition and supply (LCS)** module simulates land supply for soybean production and its resulting land-use changes. The unmanaged land-use shares database (LUCdb) provides historical patterns in managed land expansion. Additionally the crop inputs and costs (CICdb) and geo-referenced (GISdb) databases provide inputs to simulate net returns per unit of land, land productivity and suitable available agricultural land.

The **life cycle assessment (LCA)** module simulates the GES of the biodiesel. LUC GHG emissions are estimated based on simulated land-use changes in the LCS module and emission factors from the life cycle inventory database (LCIdb). The GES is then feedback to the BM module to account for the GHG emission constraints in biodiesel exports to the EU.

5.1.2. Model implementation in system dynamics

The simulation model is implemented in system dynamics. Appendix 9.2 gives a description of system dynamics theoretical foundations. Each module has a specific stock and flow structure (SFS) that is properly presented in Appendix 9.3. SFS draws on a set of conventional structures described by Sterman (2000) and including: supply-demand-price, market share and attractiveness, anchoring and adjusting, goal seeking and hill climbing search structures.

Supply-demand-price structures represent market dynamics by adjusting the price based on the supply and the demand imbalance of each soybean product. Market share and attractiveness regulate the supply of soybean products to each market destination. Anchoring and adjusting and goal seeking structures adjust the system to a desired state. These structures determine that when the gap between the desired state of a variable changes the system changes in the opposite direction. The model compares the current state of a system variable with its desired state. When a discrepancy is found, the gap - a corrective action, is performed to bring the state of the variable back in line with the desired level (Sterman 2000). The hill climbing search structures, such as the price formation, is first-order without overshoot and oscillation because the model ignores changes in inventories.

The representation of feedback loop in each causal loop diagram (CLD) follows the system dynamics conventional representation (Figure 9-1). A CLD is associated to each module to represent the main causal interaction among variables driving dynamics in each module. Dynamics arise from the interaction of input variables (from databases), variables from other modules (simulated variables) and parameters. Simulated variables are intermediate variables used to estimate outputs in each module. Appendix 9.4 details input variables and parameters of each module. The “source” indicates the variable location in the model architecture in Figure 5-1. Data sources for each module are detailed in section 5.6.

Delays create instability in dynamic systems. Adding time delays to negative feedback loops increase the tendency for the system to oscillate (Sterman 2000). Delays are present in many sectors in the model. Main delays account for the time needed to form expectation and the time needed to take action. In the simulation model, delays are introduced in the formation of prices, yields, and the supply of value-added products and land for each managed land-use type. Delays in land conversions represent the time needed by the producer to take the decision to increase supply of a specific land-use (expectation delay) and the time needed to implement the decision (action delay).

The model’s time horizon is 2001-2025, that reflects medium term projections of the system evolution. However, for sensitivity purposes, runs are typically extended to 2050 in order to reduce horizon effects. The model is calibrated to 2001 data and the historical period covers the first 10 years of the simulation (from 2001 to 2010). Historical data provides a useful test of model behaviour. Parameters are given from literature or estimated for specific model functions. Projections from other models are used as reference modes for model behaviour validation tests.

While several software products are available for system dynamics modeling, Vensim DSS® was chosen for its modeling flexibility and for license reasons. The DSS version accounts for advance features that were essential for this project, mainly the graphical interface, the ability to perform causal loops tracing, and sensitivity analysis (Ventana Systems 2010). Moreover, subscripted modeling of variables was a useful tool for model simplification.

5.1.3. Simulation procedure

The assessment of the biodiesel export potential under GHG emissions constraints is performed as follows (Figure 5-2).

Firstly, the initial conditions for the simulation are set in the initial year (t_0), considering the initial values of simulated variables, inputs, parameters, policy framework variables and the evolution of external factors set by scenario. The model is initialised in equilibrium, which means that backlogs are not considered and the system remains stable if no changes are introduced. Model equations are solved for each time step of the simulation but results are expressed in a year basis. The system responds to changes in the policy framework and the evolution of prices and demand for soybean products. Changes in policy instruments and demand shifters cause producers in the biodiesel supply chain to adjust their supply level iteratively until the final time (T) of the simulation.

The biodiesel domestic demand, simulated in the BDM module, is linked to the CD module, jointly with the international demand for AR biodiesel to estimate soybean oil demand for biodiesel production. The price of soybean oil in the international market adjusts based on the quantity of soybean oil exported by the AR producer. This price is then linked to the BM module to estimate biodiesel production costs. Given the evolution of the soybean oil international price, biodiesel producers adjust their supply level that determines the quantity of biodiesel supplied by each aggregated firm to each market. Additionally, the GES of the biodiesel, simulated in the LCA module, is linked to the BM module to estimate the fulfilment of the GES threshold imposed in the EU-RED.

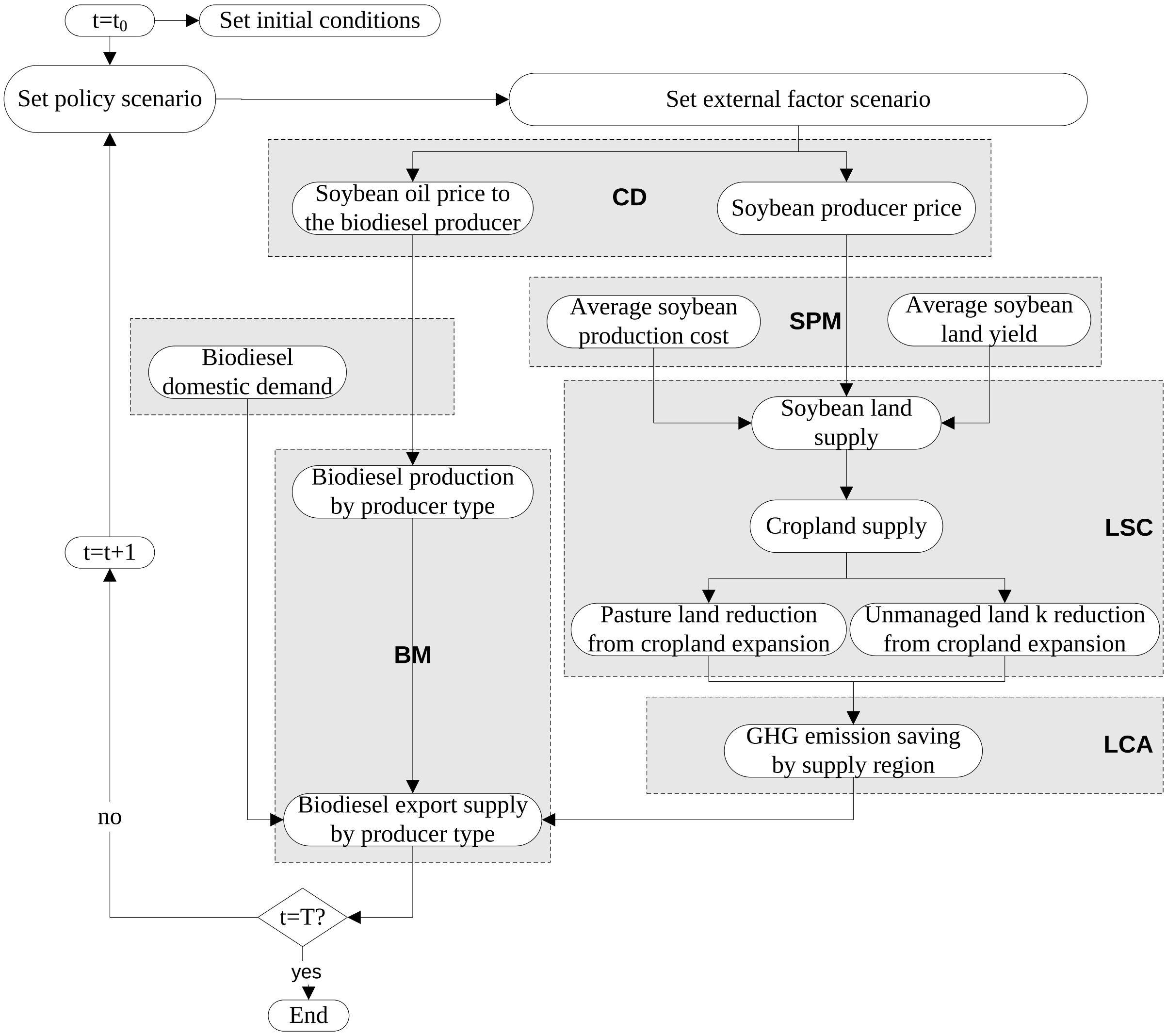

Figure 5-2. Simulation procedure.

Oil supply for biodiesel is determined by the supply of soybeans to the crusher and the soybean oil exports. The quantity of soybean oil and meal exported adjust the prices of these products in the international market. Changes in these prices define the quantity of soybeans diverted to crush. Soybean production depends on the quantity of land diverted to soybean production and the soybean yield, both simulated in the LCS module. These results are then used to estimate dLUC from soybean production for biodiesel.

Land supply for soybean production is simulated based on land allocation among competing crops and the supply of land for managed land types. The LCS module defines the expansion rate of managed lands into unmanaged lands and estimates the share of soybean land on cropland expansion. These results are used in the LCA module to estimate LUC GHG emissions.

Finally, in the LCA module, the GES is simulated based on the dLUC GHG emissions from different soybean supply regions. The GES is linked to the BM module to simulate the effect of regional soybean production patterns on the quantity of biodiesel supplied to the export market.

5.2. Biodiesel market module

The biodiesel market (BM) module assesses market dynamics in the biodiesel sector. The BM module estimates biodiesel production and the quantity of biodiesel supply to each market by each biodiesel producer type (Table 5-1). Symbol and equation indicates the variable notation and equation number in the modeling framework of Chapter 4.

The simulation procedure of the BM module is as follows (Figure 5-3). The quantity of biodiesel production and the supply of each firm to the export market are simulated based on the evolution of the values of the policy instruments, the external factors and the simulated variables over time, until the final time (T) of the simulation.

Biodiesel production depends mainly on the expected unit profit of each aggregated producer type. For each simulation step, the biodiesel production level is simulated based on the unit profit at the previous step. The biodiesel domestic price, defined as a *cost-plus pricing* policy, evolves as a function of the soybean oil producer price.

Table 5-1. Outputs and simulated variables of the BM module.

Outputs	**Units**	**Symbol**	**Equation**
Biodiesel production by producer type	ton/year	q_{bio}^{f}	Eq. 4-29
Biodiesel export supply by producer type	ton/year	$q_{bio}^{f-\exp}$	Eq. 4-38
Simulated variables	**Units**	**Symbol**	**Equation**
Biodiesel domestic supply by *s&m* firm	ton/year	$q_{bio}^{s\&m-bl}$	Eq. 4-35
Biodiesel domestic supply by *lg* firm	ton/year	$q_{bio}^{\lg-bl}$	Eq. 4-37
Fulfilment of EU-RED EST	-	Constraint	Eq. 4-38
Aggregated biodiesel unit profit	US$/ton	g_{bio}^{bp-f}	Eq. 4-39
Biodiesel export producer price	US$/ton	$P_{bio}^{\exp}$	Eq. 4-32
Biodiesel domestic producer price	US$/ton	P_{bio}^{dom}	Eq. 4-33
Biodiesel international price	US$/ton	P_{bio}	Eq. 4-5
Soybean oil supply for biodiesel	ton/year	q_{oil}^{bp}	Eq. 4-30
Oil price to the biodiesel producer	US$/ton	P_{oil}^{bp}	Eq. 4-34
AR Biodiesel international demand	ton/year	$q_{bio}^{\exp}$	Eq. 4-11

Once the production level of each producer type is defined, biodiesel production is allocated among market destinations. This decision depends on the domestic biodiesel demand, simulated in the BDM sub-module and the quota for *s&m* firms. The desired biodiesel export supply is then found, based on the production level and the supply of each firm to the domestic market.

Finally, biodiesel exports are constrained by the fulfilment of the GHG emission saving threshold fixed by the EU. If the criteria is fulfilled each biodiesel producer supplies its desired exports to the international market. Otherwise, the biodiesel export supply is zero.

The dynamics in the biodiesel international market determine the biodiesel international price. The intersection of the simulated export supply and international demand for the AR biodiesel determine the international price of the biodiesel. The new equilibrium price, adjusted by the exogenous price trend, is used in the next simulation step (t+1) to estimate the new production level of each firm and the international demand for AR biodiesel.

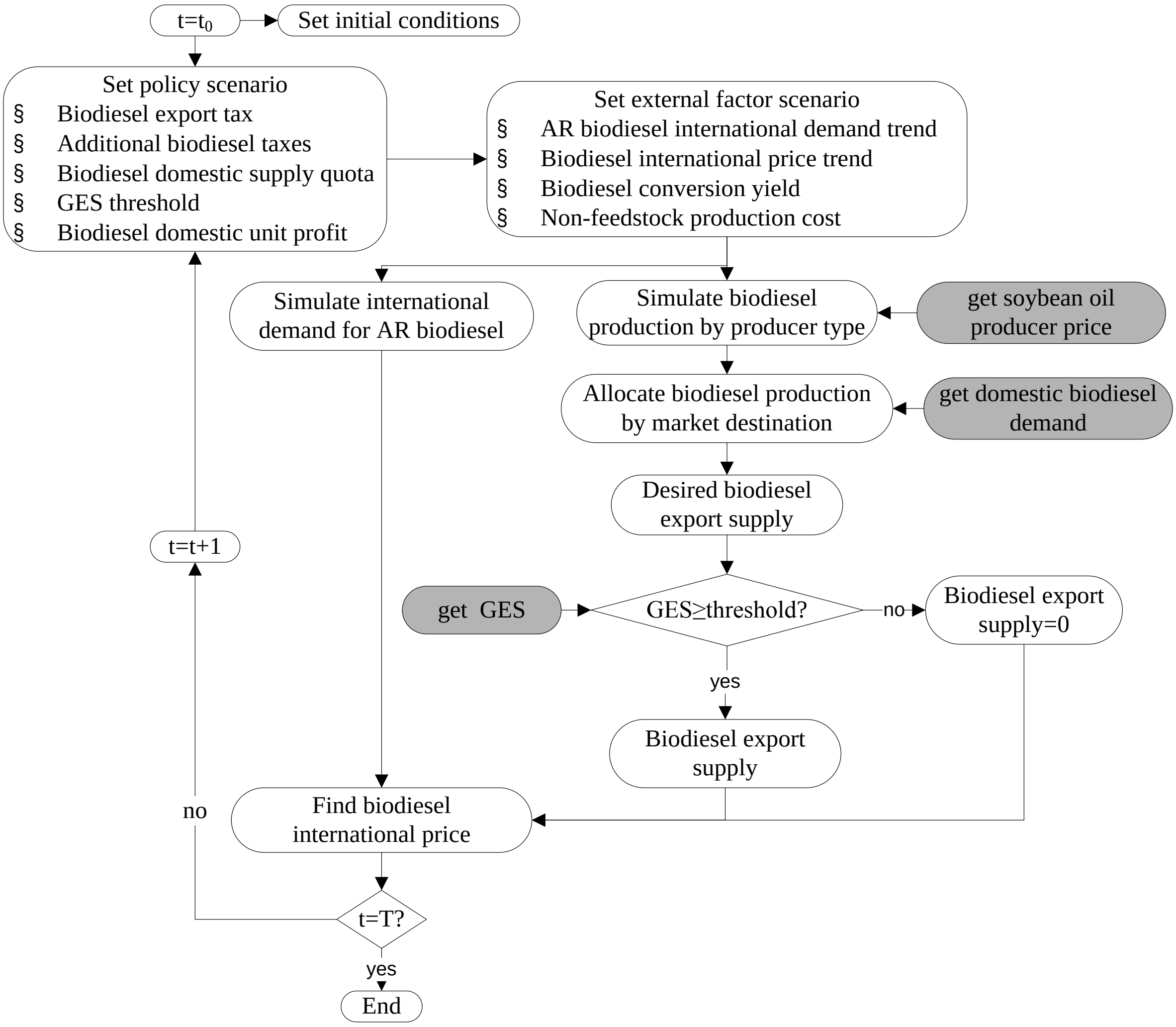

Figure 5-3. Simulation procedure of the BM module.

The BDM sub-module simulates biodiesel domestic demand (Table 5-2). The fuel price adjusts to the evolution of the fuel demand of the aggregated domestic fuel consumer (Figure 5-4). In the initial year biodiesel domestic demand is zero. When the blending target policy is implemented the biodiesel domestic demand of the domestic aggregated blender is defined. The evolution of the shifter for the domestic fuel demand determines the evolution of the domestic fuel demand. The simulation is repeated each time until the end of the simulation period (T).

The SFS of the BDM includes only one stock, namely the diesel price (Figure 9-3). The diesel and biodiesel prices to the blender are estimated based on the set of policy instruments regulating the domestic fuel market. The diesel price adjusts through an *anchoring and adjust* structure that finds the equilibrium price based on the supply-demand imbalance in the domestic market.

Table 5-2. Outputs and simulated variables of the BDM module.

Outputs	**Units**	**Symbol**	**Equation**
Biodiesel domestic demand	ton/year	$q_{b\,io}^{bl}$	Eq. 4-12
Simulated variables	**Units**	**Symbol**	**Equation**
Fuel domestic demand	ton/year	q_{fuel}^{c}	Eq. 4-13
Fuel domestic price	ton/year	P_{fuel}^{c}	Eq. 4-14

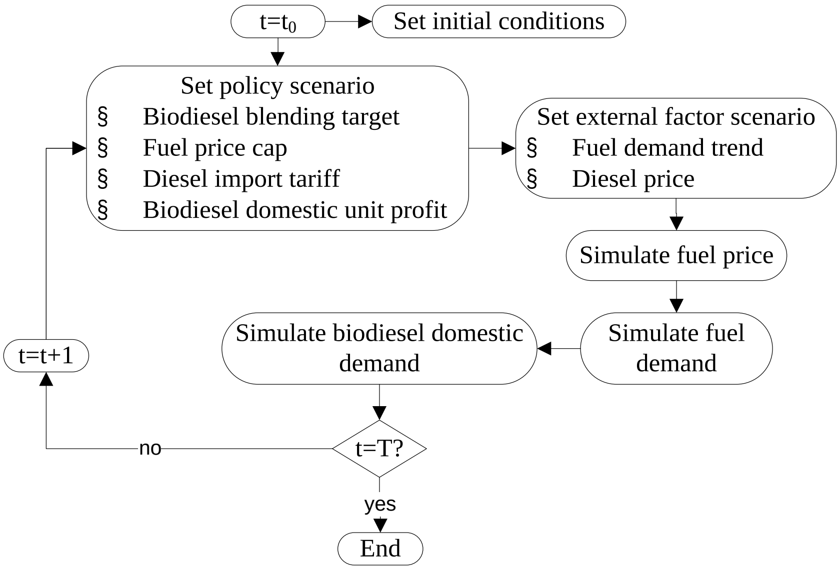

Figure 5-4. Simulation procedure of the BDM sub-module.

In the BM module, variable interaction create feedback structures affecting the biodiesel export potential (Figure 5-5). Feedback structures along with other exogenous variables drive the allocation of biodiesel production by producer type and market destination. Four feedback loops are identified in the BM module, namely:

- R1: Market allocation of biodiesel production
- B1: Biodiesel international demand adjustment
- B2: Biodiesel export supply adjustment
- B3: Effect of the GES threshold on biodiesel exports

Biodiesel allocation between market destinations creates a reinforcing feedback structure (R1) so that increasing biodiesel supply to the domestic market reduces the availability of biodiesel for the international market and vice-versa. Loops B1 and B2 account for the classical feedback structure in commodity markets (Sterman 2000).The international demand for AR biodiesel adjusts to changes in the international biodiesel price, creating a balancing feedback loop (B1). In this feedback, the international demand for AR biodiesel decreases as the biodiesel price increases in the international market. An increase in the biodiesel international price, in turn, decreases the international demand for the AR biodiesel. The interaction between the international biodiesel price and AR biodiesel export supply creates a second negative feedback loop (B2). In this case, the international biodiesel price decreases as supply by AR biodiesel producers to the international market increases and vice-versa.

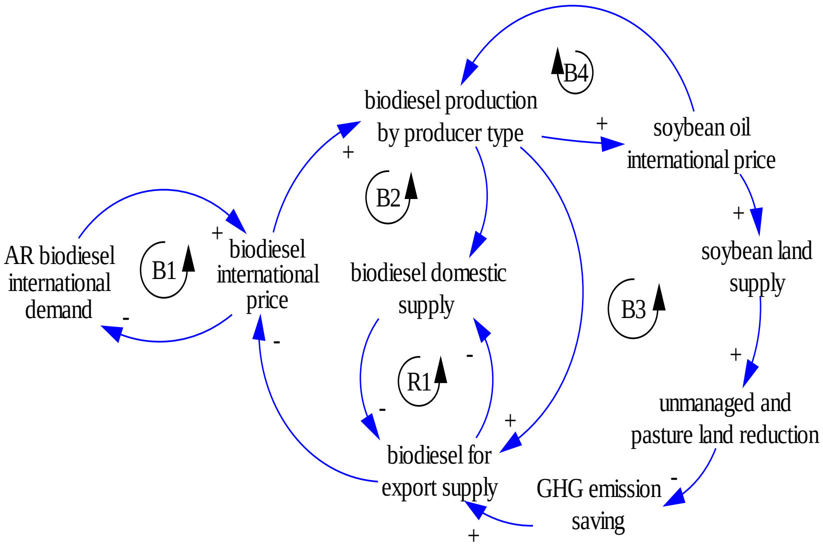

Figure 5-5. Feedback loops in the BM module.

For the purpose of this research, the critical feedback structure regulating the biodiesel export potential is a negative balancing loop (B3) that constraints the quantity of soybean-based biodiesel exported based on the GES of the biofuel. This loop is the linkage among the four modules in the simulation model and works as follows. If biodiesel production in Argentina for the domestic and the international markets increases soybean oil (and meal) supply, so that more land is diverted to soybean production, the induced land-use changes may reduce the GES of the biofuel. In this case, biodiesel exports to the EU may be constrained if the GES does not comply with the GES threshold imposed in the EU-RED. Alternatively, a reduction in the supply of biodiesel to the international market may reduce land supply for soybean production reducing LUC and therefore increase the GES of the biodiesel. Indeed, this is the intended purpose of the EU-RED.

The balancing loop regulating the effect of oil demand for biodiesel production on the oil international price (B4) is assessed in the CM module.

The SFS of the BM module is as follows. Biodiesel supply to each market is modeled as a stock that accumulates the change in biodiesel supply to each market (Figure 9-4). Biodiesel producers are disaggregated in *s&m* and large producers (subscripted variables), so that each stock accounts for the accumulation of biodiesel supply by each producer type. Flows of biodiesel supply change based on the evolution of the domestic and export demands and the market share of each firm in each market. Flows adjust with a delay that accounts for the time needed to make the investment decision and the time needed to construct the biodiesel plant. Different delays for large and *s&m* plants are specified, assuming large plants take more time to be operational.

5.3. Crushing dynamics module

The crushing dynamics (CD) module assesses market dynamics in the crushing sector. This module estimates the supply response of the aggregated AR crusher and AR soybean producer to demand and price changes of soybean, oil and meal. The module generates three main outputs (Table 5-3). Simulated variables endogenously determine the producer price of each soybean product.

Table 5-3. Outputs and simulated variables of the CD module.

Outputs	Units	Symbol	Equation
Soybean production	ton/year	q_{soy}^{sp}	Eq. 4-16
Soybean producer price	US$/ton	P_{soy}^{sp}	Eq. 4-18
Soybean oil price to the biodiesel producer	US$/ton	P_{oil}^{bp}	Eq. 4-34
Simulated variables	**Units**	**Symbol**	**Equation**
Crush margin	US$/ton	g^{cr}	Eq. 4-26
Soybean supply for crush	ton/year	q_{soy}^{cr}	Eq. 4-25
Soybean oil production	ton/year	q_{oil}^{cr}	Eq. 4-23
Soybean meal production	ton/year	q_{meal}^{cr}	Eq. 4-24
Soybean, oil and meal exports	ton/year	$q_{o}^{\exp}$	Eq. 4-6
Soybean, oil, meal international price	US$/ton	P_{o}	Eq. 4-5
AR Soybean, oil, meal international demand	ton/year	q_{o}^{c}	Eq. 4-4

The quantity of soybean production is used in the LCS module to allocate dLUC from soybean production for biodiesel. The soybean producer price is linked to the LCS module to estimate the soybean land unit profit. The soybean oil producer price is linked to the BM module to estimate the soybean oil price to the biodiesel producer.

The simulation procedure of the CD module is described as follows (Figure 5-3). The production of soybeans, the soybean producer price and the soybean oil price to the biodiesel producer are iteratively simulated based on the evolution of the values of the policy instruments and the external factors and the simulated variables over time, until the final time (T) of the simulation.

Given the evolution of external factors and the given international price, the international demand for AR soybean, oil and meal is defined; then, the current supply of soybean at this price level is simulated. Soybean supply is then allocated between market destinations based on soybean demand for crush. The quantity of soybean oil exports is then simulated based on the domestic supply of soybean oil for biodiesel production. Finally, the new price level is found based on the intersection of the AR supply curve and the international demand curve for soybean oil and meal respectively. In the next simulation step (t+1), the new demand and supply levels are simulated based on this new price level and the evolution of demand for soybean oil and meal.

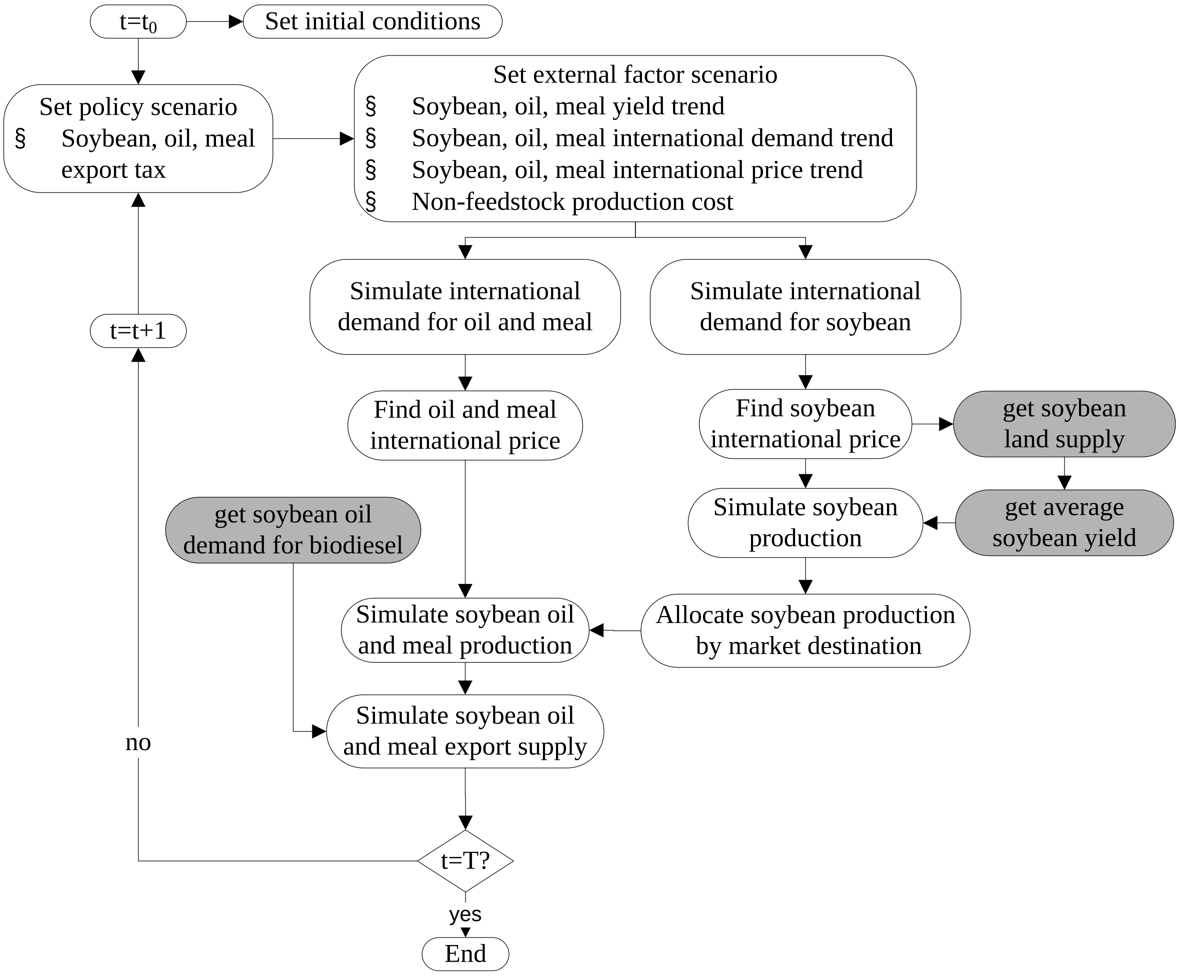

Figure 5-6. Simulation procedure of the CD module.

Two negative balancing feedback loops regulate the price adjustment mechanism based on changes in the supply by the aggregated producer and the demand by the aggregated final consumer for AR soybean products in the international market. This generic feedback structure is applied to each product in the crushing sector (Figure 5-7). Consequently six negative feedback loops are identified in the crushing dynamics module, grouped in two types:

- B4, B5, B6: Soybean, oil and meal AR export supply adjustment
- B7, B8, B9: Soybean, oil and meal international demand adjustment

In the crusher dynamics module, these loops work as follows. If the international demand for soybean oil and meal increases *ceteris paribus*, the international price of each product increases given the current supply by the AR producer. Raising soybean oil and meal prices drive an increment in the crush margin and consequently in the quantity of soybean diverted to crush. Soybean supply for crush also adjusts to the supply and demand balance of soybean in the international market.

Raising soybean supply for crush increases soybean oil and meal production and, *ceteris paribus*, reduces the export of soybeans on the other hand. Analogously to soybean oil and meal prices, the soybean international price adjusts also to changes in structural factors and the supply and demand balance for AR soybeans in the international market. As soybean oil and meal supply increase, in the absence of other changes, the export of these products also increases. In this context the allocation of soybean oil for biodiesel production reduces soybean oil exports. The soybean oil international price consequently rises to increase soybean oil exports. As the export supply increases, prices are bid downwards.

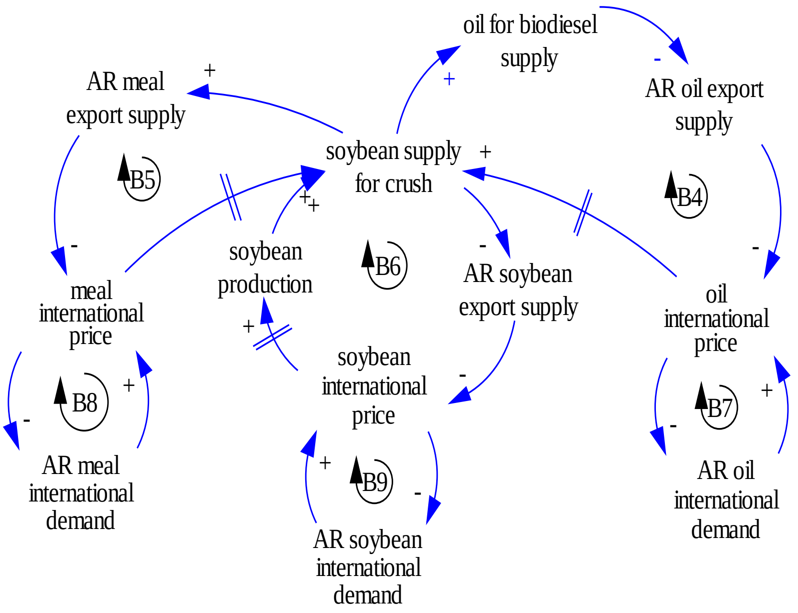

Figure 5-7. Feedback loops in the CD module.

In conclusion, loops B4, B5 and B6 adjust the production level of the aggregated AR producer based on the effect of price on the producer unit profit and loops B7, B8 and B9 adjust the international demand level for AR soybean products based on the effect of price on consumer utilities. These two negative feedback loop types cause price to adjust until, in the absence of further external shocks, the market reaches equilibrium with production equal to consumption.

The crush margin adjusts with a delay needed to form expectations and make a decision. Oil and meal production adjust with a delay caused by the time need for instance, to adjust the capacity utilisation and the installed capacity. Soybean production adjusts with a delay given by the time need to form land profit expectation and decide on the desired quantity of land diverted to soybeans.

In the crushing dynamics module, the critical stock and flow structure is the price formation structure and its effect on AR supply of soybean products (Figure 9-5). International prices are modeled as stocks. Soybean, oil, and meal international prices adjusts to the indicated international price through goal seeking structures (Sterman 2000). Discrepancies in the supply-demand balance are solved by adjusting the price levels of each product based on the supply response of the AR firm and the demand level of the AR product in the international market.

5.4. Land competition and supply module

The land competition and supply (LCS) module simulates land supply for soybean production and its resulting land-use changes. The LCS module generates five main outputs that are successively used in the CM and LCA module to estimate soybean production and LUC GHG emissions from soybean production for biodiesel use (Table 5-4).

In the CM module, soybean production is given by the supply of land for soybean production and the average soybean yield, both simulated in the current module. Additionally, GHG emissions from land-use change and soybean cultivation also depend on the average soybean yield in each region, so, the average soybean yield is also linked to the LCA module. The LCS module then estimates the quantity of land converted from each unmanaged land-use *k* and pastureland to cropland. dLUC GHG emissions from cropland expansion need to be allocated to soybean production for biodiesel. Therefore the LCS module also estimates the share of soybean on cropland expansion.

Table 5-4 . Outputs and simulated variables of the LCS module.

Outputs	**Units**	**Symbol**	**Equation**
Soybean land supply	ha/year	q_{land}^{sp}	Eq. 4-41
Average soybean land yield	ton/ha	Y_{soy}^{sp}	Eq. 4-19
Unmanaged land *k* reduction from cropland *l* expansion	ha/year	$q_{l,k}$	Eq. 4-45
Pasture land reduction from cropland expansion	ha/year	$q_{l,l}$	Eq. 4-46
Cropland supply	ha/year	q_{land}^{l}	Eq. 4-43
Simulated variables			
Soybean land unit profit	US$/ha	g_{land}^{n1}	Eq. 4-17
Pasture land unit profit	US$/ha	g_{land}^{l2}	Eq. 4-3
Competing crop unit profit	US$/ha	g_{land}^{n2}	Eq. 4-3
Competing crop land supply	ha/year	q_{land}^{cc}	Eq. 4-41
Pasture land supply	ha/year	q_{land}^{l2}	Eq. 4-43

Simulated variables account for 1) the estimation of land-unit profits of each competing crop and managed land-use type, 2) the resulting land supply for each land-use type based on the competition among managed land-uses.

The simulation process of the LCS module is shown in Figure 5-8. The dynamics of the LCS module arise from determining the rates of change in land supply for each land-use type.

The first task to be performed is the estimation of the unit land profit of each crop type (i.e. soybean, corn). Then provided that production costs and export taxes allow soybean producers to get positive profits and depending on the unit profit of competing land-uses, cropland is allocated between soybean and corn. Land stocks of competing crops increase when their own land unit profit increases and decrease when the land unit profit of the competing crop increases.

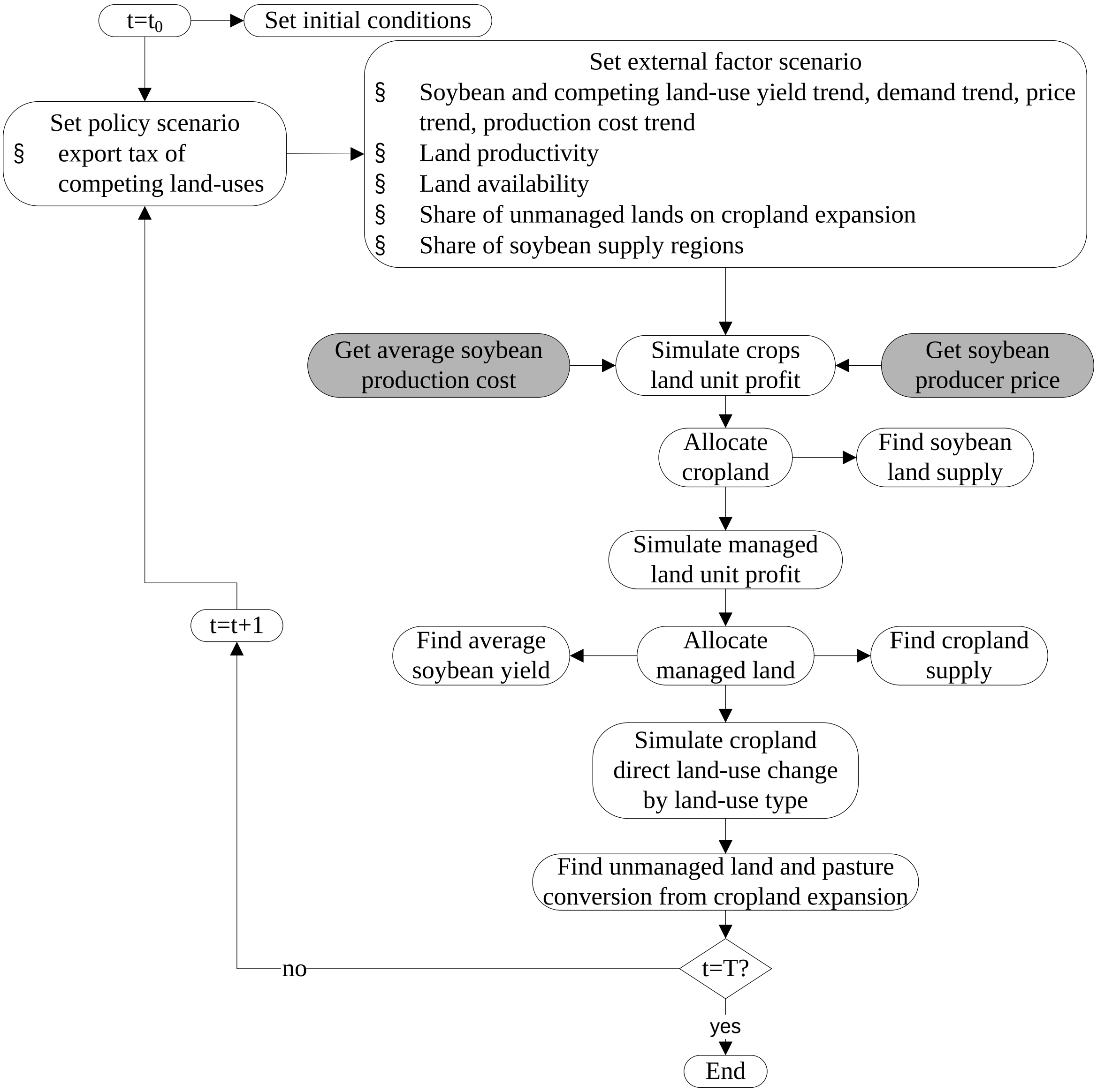

Figure 5-8. Simulation procedure of the LCS module.

Managed land is then allocated between cropland and pasture based on their aggregated land unit profits. The level of cropland supply defines the effect of land productivity on the yield of soybean, corn and pasture.

Finally, direct land-use changes from cropland expansion are simulated to estimate the quantity of cropland expansion into each unmanaged-use type and pastureland. Unmanaged lands decrease with cropland and pasture expansion. No natural regeneration is assumed, consequently, unmanaged lands are only allowed to be reduced. Expanding into degraded lands may lead to lower yields but also to lower carbon stock changes. In contrast, expanding agricultural land into forest may lead to the release of significant carbon stocks which may negatively affect the biodiesel GES.

The LCS module is linked to the SPM sub-module. The SPM module is a set out auxiliary variable (Figure 9-8) which determines the production costs and the soybean yield for each soybean region (Table 5-5). Auxiliary variables are assumed constant, so that changes in soybean production costs depend only on the share of cultivation methods by region. No feedback structures are present in this sub-module.

Table 5-5. Output variables of the SPM sub- module.

Outputs	**Units**	**Symbol**	**Equation**
Soybean land unit production cost by region	US$/ha	$C_{soy,sr}^{sp}$	Eq. 4-21
Soybean land yield by region	ton/ha	$Y_{soy,sr}^{sp}$	Eq. 4-19

The simple simulation procedure is given in Figure 5-9.

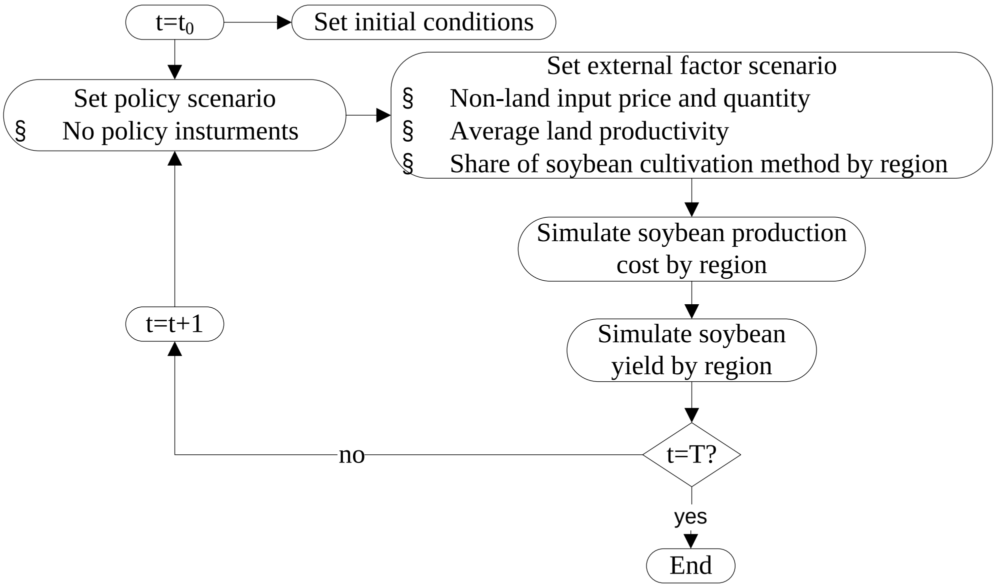

Figure 5-9. Simulation procedure of the SPM sub-module.

The complexity in land competition arises from multiple interactions among competing land-uses (Figure 5-10). Two main feedback structures are identified including the effect of competition among land-uses and the effect of land productivity on yields, namely:

- R2, R3: Cropland and managed land competition
- B10, B11: Effect of land productivity on managed land yield

In the first case, if cropland expansion is constrained, soybean and other crops compete for cropland based on their relative land unit profits, creating a reinforcing feedback loop (R2). The same mechanism of land competition applies for cropland and pastureland. As cropland expands, *ceteris paribus*, less land is available for pastureland, creating also a reinforcing loop (R3). Similarly, cropland and pastures compete for managed lands based on their aggregated land unit profit. For simplicity, Figure 5-10 avoids the representation of the price linkage with supply and demand for each land-based product. Beef, other crops and soybean prices however, adjust to changes in structural factors and the price effect, similarly to price adjustments loop in the crushing dynamics module. The stock and flow structure in Figure 9-6 shows these interactions.

The land productivity effect is captured in two additional balancing loops (B10, B11) that affect yields, land profits and consequently land supply for managed lands. If managed lands expand into less productive lands, yields may decrease depending on the yields trend evolution. Consequently, the productivity effect feedbacks into the producer decision to increase land supply for managed land-uses. Alternatively, as land productivity decreases, it is more difficult to bring land into production, generating higher incentives to use non-land inputs (e.g. fertilisers). For simplicity, this effect is assumed to be captured in exogenous yield trends. The counterpart of substituting land by non-land inputs is that non-land inputs costs may increase, decreasing land profits and consequently land demand.

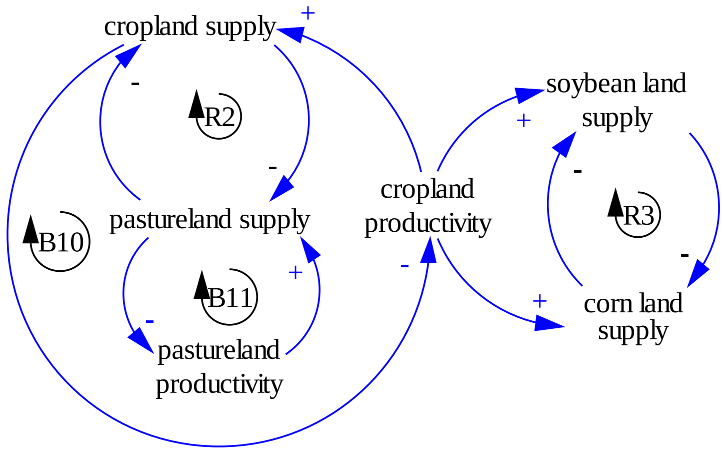

Figure 5-10. Feedback loops in the LCS module.

The land competition module is also a set of interconnected stocks and flows. There are three types of stocks: competing crops, managed lands and unmanaged lands. Competing crops account for soybean and corn land stocks that add up in a cropland stock. Managed lands account for cropland and pasture land stocks. Similarly, cropland and pasture sum up in an aggregated managed lands stock (Figure 9-6). Unmanaged land is disaggregated in six stocks accounting for forest, grassland, savannas, shrubland, mixed land and degraded land (Figure 9-7). The soybean land stock changes based on land supply for cropland and the share of soybean on cropland that depends on the relative land unit profit between soybean and corn.

Delays in land supply differ among land-use categories. Following land conversion possibilities, it is assumed that changes in competing crops adjust faster than changes in managed lands. Similarly, changes in managed lands adjust faster than changes in unmanaged lands. Delays are assumed to account for the time needed to take the decision of increasing or decreasing a particular land-use and the time needed to make the land conversion.

5.5. Life cycle assessment module

The LCA module simulates the biofuel GES (Table 5-6) and includes the estimation of the biodiesel GHG emissions from LUC and soybean cultivation. The GES is linked to the BM module to estimate the fulfilment of the GES threshold.

The LCA model is based on earlier work, by “dynamising” an attributional LCA of soybean-base biodiesel production for export in Argentina (Panichelli *et al.* 2009). The methodology, however, was adapted based on the European methodology for LCA GHG emissions estimations in biofuel pathways (EC 2009). Table 5-7 gives the specifications of the LCA module.

Table 5-6. Outputs and simulated variables of the LCA module.

Outputs	**Units**	**Symbol**	**Equation**
GHG emission saving by supply region	%	$er_{bio,sr}$	Eq. 4-52
Simulated variables			
GHG emission balance of the biofuel	gCO2eq/MJ	$e_{bio,sr}^{bp}$	Eq. 4-49
LUC GHG emissions from biodiesel supply	gCO2eq/MJ	el_{sr}	Eq. 4-50
GHG emissions from soybean cultivation by method	gCO2eq/MJ	eec^{m}	Eq. 4-51

Table 5-7. Specifications of the LCA module.

Modeling assumptions	**Description**
System definition	Well-to-Wheel
Allocation method	Energy/Economic
Functional unit	gCO2eq/MJ
Reference land-use	Based on simulated land-use changes from LCS
Reference fossil fuel	EU fossil diesel reference
Unit processes	Soybean production Oil extraction (soybean crushing) Oil transesterification (biodiesel production) Biodiesel transport and distribution Biodiesel use
LCIA method	IPCC 2001 GWP 100a (climate change)
LCI data	ecoinvent® 2.01 database
GHG emission gases	carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O)
CO2 equivalence	CO2:1 N2O :296 CH4 :23
LUC emissions amortisation	20 years

The AR soybean-based biodiesel GHG emission balance was modeled through an LCA and was compared with the reference fossil diesel value given in the EU-RED. The system is modeled based on a well-to-wheel approach, which means that the model accounts for GHG emissions from the feedstock production to the biofuel use. The function unit was specified as gCO2eq per energy unit, as required in the EU-RED. The system was divided into five unit processes, including the main production stages of the biodiesel supply chain. Energy allocation is the default setting of the LCA allocation approach. Nonetheless, an alternative allocation case was simulated based on economic value to evaluate the variability of results with regard to this key methodological parameter. Economic allocation was based on the simulated producer prices of each soybean product in the biodiesel supply chain, with the exception of glycerine, where a constant price was used.

The life cycle inventory (LCI) and the life cycle impact assessment (LCIA) were performed in Excel spreadsheets using the ecoinvent ® 2.01 database and then integrated as constants into the dynamic simulation model. GHG emission gases and their respective CO2 equivalence are also specified according to the EU-RED methodology. Emissions from each unit process include emissions from the production process itself; from the collection of raw materials; from waste and leakages; and from the production of chemicals or products used in extraction or cultivation. CO2 uptake in the cultivation of soybean was excluded and emissions from fuel use are assumed to be zero.

In the dynamic simulation model, the LCA module does not present any specific stock and flow structure (Figure 9-9 -Figure 9-11). The module is mainly a set of auxiliary variables. The interconnections between them determine the GHG emission balance for each unitary process of the biodiesel supply chain. While no policy variables are included in the LCA module, the module accounts for some critical methodological option in LCA of biofuel pathways such as economic and energy allocation, land-use change accounting and functional unit choice.

The simulation of the GHG emission saving is as follows (Figure 5-11). Firstly, LUC GHG emissions from cropland expansion are estimated based on simulated land-use changes in the LCS module. LUC GHG emissions from cropland expansion are estimates based on the supply of cropland from unmanaged land-uses and pastureland, given by the LCS module (following the B4 feedback loop). Instead of giving a credit for soybean cultivation in degraded land[38], the model simulates GHG emission savings from cultivation in degraded land. Emissions from cropland expansion are then allocated to soybean for biodiesel based on the share of soybean on cropland expansion and the share of soybean for biodiesel on soybean land supply, which are endogenous variables given by the LCS module.

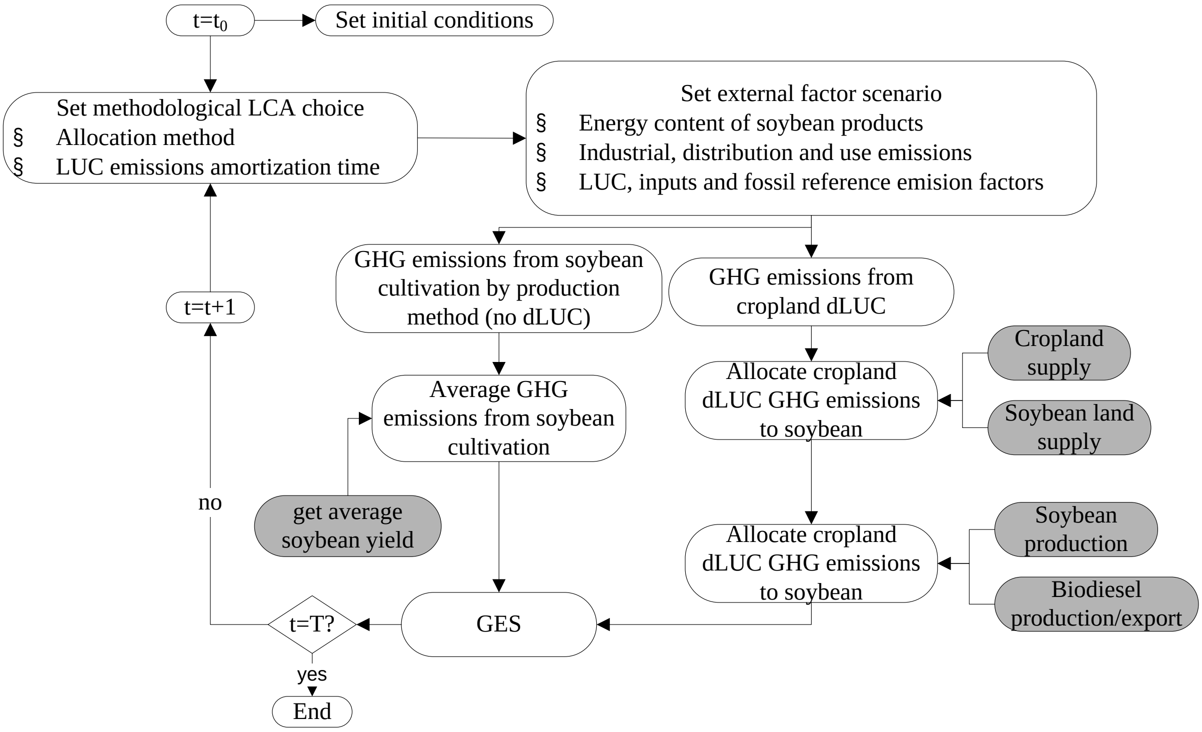

Figure 5-11. Simulation procedure of the LCA module.

GHG emissions from soybean cultivation are estimated based on the three main soybean production systems in Argentina (*font*, *sont*, *foct*). Diesel consumption in agricultural processes was converted into inputs of agricultural field work processes according to ecoinvent® (Nemecek *et al.* 2007) in order to consider agricultural machinery production and

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[38] The EU-RED assigns a bonus of 29 gCO_{2eq}/MJ biofuel or bioliquid if biomass is obtained from restored degraded land under certain conditions specified in vided for in point 8.

use as well as exhaust emissions from the tractor. Pesticide and fertiliser use is the average of soybean cultivation in Argentina under the different production systems. Nitrogen fertiliser is only applied to first occupation soybean as monoammonium phosphate (MAP), whilst second occupation uses the residual fertilisation of the previously implanted crop. P fertiliser is applied as MAP and triple super phosphate (TSP) fertilisers. N2O emissions are calculated as a direct emission from the N input and an indirect emission from the N content in nitrate leaching, as implemented in ecoinvent®. N input accounts for the N biological fixation (BNF) and for N fertiliser (Jungbluth *et al.* 2007). Transport distances are adjusted for each soybean production region, based on the distance to the Rosario, where most of the crushing facilities are located.

Industrial emissions from soybean oil crushing and transesterification are based on emissions from average international technology. Solvent extraction technology (with methanol) and soybean oil transesterification (with hexane) is based on international standard technology, as described in Jungbluth *et al.* (2007) for biodiesel production. However, yields, allocation factors, natural gas and electricity consumption, electricity mix and transport distances are specific to the Argentinean context. No data was available for the soybean intermediate storage and drying phase. Consequently, this stage was not considered in the system boundaries, and it was assumed to take place only at the vegetable oil extraction plant. No difference was assumed between biodiesel and fossil diesel in useful work done in the estimation of biodiesel use emissions.

Finally, total emissions from biodiesel production are estimated as the sum of emissions of each unitary process to simulate the biodiesel GHG emission balance. The GES is then estimated based on the reference fossil diesel emission factor. The GES of the biodiesel is linked to the BM module to estimate the biodiesel export potential under the GES threshold imposed in the EU-RED.

5.6. Data and calibration of parameters

Several data sources have been used to calibrate model parameters. Model parameters account mainly for elasticity values, time delays and initial conditions.

5.6.1. Biodiesel supply chain parameters

Initial international prices, supply by AR firms and international demand for soybean products, corn and beef are estimated based on the FAPRI Agricultural Outlook (FAPRI 2010a). Initial production costs for competing activities were obtained from a study by Agromercado (2010). Production inputs uses and costs for soybean production under each method were obtained from average regional data published by Márgenes Agropecuarios (2006). Initial cost data for the aggregated crusher and each biodiesel producer are taken from CADER (2011) and SE (2010b). Soybean oil, meal and biodiesel conversion yields are taken from FAPRI (2010a).

The crush margin elasticity is estimated based on the FAPRI elasticity of soybean demand to crush margin (FAPRI 2010a). No consistent data was found to estimate the biodiesel unit profit elasticity for each producer type. Consequently, this parameter was calibrated based on the international biodiesel price and the aggregated biodiesel supply to the international market. However, a lower elasticity value was set for the aggregated *s&m* biodiesel producer. Sensitivity analysis is performed to test the effect of different elasticity values.

5.6.2. Land supply and land-use change parameters

Initial soybean, other crops and pasture land stocks are calculated based on the Ministry of Agriculture statistical database (INDEC 2002; MAGPyA 2010). Suitable available agricultural land was estimated based on the FAO land-use database (FAO 2010). Unmanaged land initial stock values were calibrated based on values given in the ICF model (ICF 2009).

The effect of competing land profit (soybean and corn) on indicated land is based on land supply elasticities obtained from the FAPRI elasticities database (FAPRI 2010a). Note that FAPRI elasticities are in response to prices and not to profits. Land elasticity values were calibrated to fit historical data on land supply for each crop. Land transformation elasticities are based on values given in the OECD PEM model (OECD 2003). Elasticities, however, are not available for the Argentinean case. Consequently, following on from work undertaken by Bouet *et al.* (2010), the model assumed elasticity values for the Mexican case.

The land productivity curve for cropland and pasture land is calibrated following the approach by van Meijl *et al.* (2006). To this end, geo-referenced land productivity data is extracted from the agricultural land productivity map included in the IMAGE model (MNP 2006). The Argentinean land productivity data was extracted from the global map, converted into point data, extracted to Excel and then sorted in decreasing order to generate a land productivity curve for the national territory. The land productivity curve is normalised between 0 and 1 indicating the increment factor from the potential crop yield.

Historical land-use changes are obtained from the ICF model (ICF 2009) used in the EPA integrated modeling framework (EPA 2010b). The ICF model is based on MODIS world satellite images classification. ICF has extracted and reclassified the images to quantify land-use changes for each region of the world between 2001 and 2007 (ICF 2009). An Excel table is generated with a set of data for each State including land-use changes for each of the 10 unmanaged land-use types. This generates a list of 100 LUC combinations that are then aggregated to define the initial land-use in 2001 and the final land-use in 2007. This model assumed the same unmanaged land-use types as in the ICF model. However, unmanaged land shares were disaggregated by region, to account for different unmanaged lands expansion shares depending on the soybean supply region.

5.6.3. GHG emissions parameters

The LCA model is based on Excel and linked to the ecoinvent® database. Emission factors are from the ecoinvent database (Jungbluth *et al.* 2007). A description of the LCA inventory data is given by Panichelli *et al.*(2009). Fossil diesel emissions are taken from the European legislation (EC 2009).

Land-use emission factors are also obtained from the ICF model (ICF 2009). Emission factors are estimated for a 30 year period, implicitly considering uncertainty (Harris *et al.* 2009). Aggregated emissions for the industrial phase, transport, distribution and use are obtained from an attributional LCA of soybean-based biodiesel in Argentina (Panichelli *et al.* 2009).

5.7. Model validation and testing

Several experiments can be performed in system dynamics models for model validation and testing (Barlas 1989). Following the classification of validation tests given by Schwaninger and Grosser (2009), context, structure and behaviour validation tests have been performed. Context-related tests are addressed in Chapter 1 stating the validity of the system dynamics simulation approach to address biofuels impact on land-use change and GHG emissions (*issue identification* and *methodology adequacy* test). In summary: the need to account for feedback structures, the system evolution over time and a simulation approach justify the proposition of system dynamics as an implementation framework. These three features are well covered by system dynamics simulation.

5.7.1. Structure validation tests

The model was constructed in a sequential and iterative fashion by modules. Main modules including biodiesel market, crushing dynamics, land competition and supply and life cycle assessment were developed and tested first. Modules were then integrated and linked between each other. This procedure allowed validating each module first and finally the integrated model.

Structure validation tests were mainly performed during the modeling process. The model was constructed based on well-accepted SD structures from Sterman (2000). Model structures were examined and formal inspections of model equations were performed including *causal loops tracing*. Parameters examination and calibration is treated in section 5.6. *Extreme conditions* tests and *reality check* experiments were performed also during the modeling process, mainly accounting for initial equilibrium condition tests for stock levels in the BM, CD, and LCS modules. Moreover, the SD model was checked for *rational consistency* on land allocation, price-demand relations and GHG emissions calculations. In conclusion, structure validation tests allowed checking for inconsistencies in model structure that were iteratively corrected during the implementation process.

Boundary adequacy tests were also performed by extending model boundaries, especially to account for dynamics in the domestic biodiesel sector. A critical extension, however, may be the inclusion of more detailed representation of the supply and demand dynamics in the competing land-use rectors. The model represents actors as single aggregated agents. This aggregation level is consistent with the model purpose. Moreover, actors' disaggregation in the biodiesel industry allowed accounting for specific government policies regulating the biodiesel industry. The land-use sector accounts for the main land-use types that are significant in estimating GHG emissions from land-use change. Extending model boundaries to improve the accounting of pastures and competing crops dynamics may improve our understanding of land-use change effects of soybean production. Additionally the model was tested for *units' consistency*.

Note that model validity tests needs the input from experts to validate mental models, modeling structures and model behaviour. Several experts were contacted during this research to gather data and validate hypotheses. A list of experts is provided in Appendix 9.8. However, additional feedback is still needed to improve causal loop diagrams and model structures. At the time of this research being written, this was the highest level of accuracy that could be obtained. The rest of this section is dedicated to *behavioural tests*.

5.7.2. Behaviour validation tests

Simulation experiments were performed to test model behaviour over an increased time horizon. Time horizon extension allows checking for abnormal behaviour. To this end, the model horizon was extended to 2050. No abnormal behaviour seems to appear by extending the time horizon of the model.

In general, model behaviour in continuous time should be independent of the time interval and integration method used to simulate it (Fiddaman 1997). Moreover, for accurate integration, the time interval of the simulation must be significantly shorter than the shortest time constant in the model (Sterman 2000). The default settings of the model are based on Euler integration with a time step of 0.0625. The model sensitivity to the integration method was assessed by experimentation with alternative integration algorithms, available in Vensim®. Simulation experiments were performed with varying integration method (Runge-Kutta, Euler and Difference) and reduced time steps (0.0625, 0.03125, 0.015625, 0.0078125). No significant differences were found by varying integration method, or by changing time step.

The simulation model includes several parameters. Many of these are redundant coefficients used to adjust units, set initial conditions, trivial switches for test inputs and modeling options (e.g. emissions allocation method, land-use change accounting). The remaining parameters are subject to significant uncertainty, so it is important to assess their impact on model outputs.

Key parameters account mainly for elasticities values. Sensitivity analysis of elasticity parameters is performed using random uniform probability distributions. Sensitivity analysis is performed based on the multivariate approach (Ventana Systems 2010). Univariate analysis allows testing the impact of each parameter, *ceteris paribus*. This approach allows determining the parameters which play the main role in determining the systems' behaviour (Ventana Systems 2010). Univariate analysis, however, lacks the ability to capture variables interactions, an issue that can have important implications in model results. Consequently, multivariate sensitivity analysis is used to capture this effect.

6. Simulation experiments

6.1. Overview of simulation experiments

Based on the analysis of market dynamics in Chapter 2, and the modeling framework proposed in Chapter 3, the system dynamics simulation model described in Chapter 4 was used to simulate the Argentinean biodiesel export potential to the European Union. The assessment allows estimating the quantity of biofuel that Argentina may be able to export by fulfilling the GES threshold imposed in the EU-RED.

Two main issues should be defined prior to performing simulations. The first one is the definition of the current policy framework. The second issue to be considered is the evolution of external factors. The current policy framework is set to account for the main policy instruments affecting the biodiesel supply chain (section 6.2). The evolution of external factors is set in a single representative scenario of the plausible evolution of markets for soybean, value-added and competing products (section 6.3).

The assessment of the biodiesel export potential under GHG emission constraints is performed as follows. Firstly, biodiesel production and supply to each market destination and by each producer type is assessed. Then the assessment focuses on the crushing sector to test how biodiesel production influence land supply for soybean production. Based on the aggregated soybean land supply, land-use changes induced by soybean production are simulated. The resulting GHG emissions from land-use change are estimated to determine the biodiesel GES. Finally, the biodiesel export potential is assessed by comparing the biodiesel GES with the threshold imposed in the EU-RED.

Different cases are simulated to assess the impact of biodiesel production on land-use change and GHG emissions (Table 6-1). A reference (REF) case is firstly simulated. The REF case is the simulation result of the behaviour of actors given the plausible scenario of evolution of external factors and the current policy framework.

Alternative cases include the effect of biodiesel demand and supply policies, land-use regional patterns, and GHG modeling choices. Results differ among biodiesel producer types and soybean supply regions. Simulations focused on the effect of government policies on biodiesel and land supply (sections 6.4 and 6.5) and the effect of soybean production patterns on LUC and GHG emissions (sections 6.6 and 6.7).

The effect of biodiesel demand policies is simulated by assuming different biodiesel blending targets for the domestic market. The cases then compare the impact of the current B7 blending target level (REF) with alternative blending targets (cases B0, B5, B10).

On the supply side, the REF case includes two biodiesel policies. The biodiesel domestic pricing (BDP) policy and the supply quota (Q) support biodiesel supply to the domestic market. Two alternative cases (BDP and Q) are then simulated to assess the effect on biodiesel production and exports of removing these policy instruments.

Additionally, the effect of accompanying policies is focused on the assessment of export taxes. Alternative values are simulated for the soybean, oil and biodiesel *ad-valorem* export taxes (cases ST, SOT, and BT, respectively). Simulations assess the effect of a tax increment on the supply of soybean products and land for soybean production.

Table 6-1. Overview of simulated cases.

Case	Acronym	Description	Section
1	REF	Reference case	6.4., 6.5., 6.6., 6.7.
		Biodiesel demand policies	
2	B0	No blending target	6.4.
3	B5	5% blending target	6.4.
4	B10	10% blending target	6.4.
		Biodiesel supply policies	
5	BDP	Removal of biodiesel domestic pricing policy	6.4.
6	Q	Removal of biodiesel domestic supply quota	6.4.
		Export tax policies	
7	SOT	10% increment of soybean oil *ad-valorem* export tax	6.4., 6.5.
8	BT	10% increment of biodiesel *ad-valorem* export tax	6.4., 6.5.
9	ST	10% increment of soybean *ad-valorem* export tax	6.4., 6.5.
		Land-use regional patterns	
10	C	Allocation of soybean land supply to the C region	6.6., 6.7.
11	NO	Allocation of soybean land supply to the NO region	6.6., 6.7.
12	NE	Allocation of soybean land supply to the NE region	6.6., 6.7.
13	SE	Allocation of soybean land supply to the SE region	6.6., 6.7.
		GHG modeling choices	
14	BDOM	Biodiesel use in the domestic market	6.6., 6.7.
15	EA	Economic allocation of GHG emissions	6.6., 6.7.

The REF case accounts also for the current share of each soybean supply region on soybean production. Soybean production is mainly concentrated in the central (C) region. Nonetheless, soybean expansion in the south-eastern (SE), north-eastern (NE) and north-western (NO) regions is increasing rapidly due to land availability constraints in the C region[39]. Different land-use change patterns and soybean cultivation methods are applied in each region. Simulations then assess how land-use change and GHG emissions are affected by changes in the share of soybean supply regions.

Finally, modeling choices in LCA affecting the biodiesel GES are addressed. The REF case assumes energy allocation and biodiesel production for the export market. Two alternative cases are simulated including the production of biodiesel for the domestic market and the economic allocation[40] of co-products through-out the biodiesel supply chain (cases DBOM and EA, respectively).

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[39] Almost all the region is already under soybean cultivation.

[40] Allocation is a methodological choice used in Life cycle assessment. It is introduced when the output of a process yields more than one product and consequently, the environmental impact of the unitary process needs to be allocated among the outputs. One way of performing this allocation is based on the economic properties of the product, i.e., value, price, shadow price. In the thesis, economic allocation stands for the allocation of GHG emissions based on the economic value of each product.

6.2. Biofuel policy framework

The REF case includes the constant policy framework, accounting for the set of policy instruments currently affecting the biodiesel, the fuel and the soybean sectors. These values were calibrated based on a review of current government policies (SyCDNA 2006; MEyP 2008; SE 2010a). The GES threshold is given in the EU-RED regulation (EC 2009). A detailed description of the policy framework in Argentina is given in section 2.3.2. Table 6-2 shows the values of the policy instruments included in the simulation model.

Table 6-2. Policy parameters for the REF case.

Control parameters*	Units	REF value
Maximum fuel price policy	dmnl	1
Biodiesel domestic price policy**	dmnl	1
Fossil diesel import tariff	%	20
Biodiesel blending target***	%	5-7
Biodiesel tax exemptions****	%	10
Soybean export tax	%	35
Corn export tax	%	25
Oil export tax	%	32
Meal export tax	%	32
Biodiesel export tax*****	%	17.5
Biodiesel supply quota for *s&m* firms	%	80
EU-RED GES threshold ******	%	35-50-60

* Maximum fuel price and biodiesel domestic price policies are yes-no policies i.e. they are in place or not. Other policy instruments can change in value.

** The biodiesel domestic price change based on the international soybean oil price.

*** 5% (B5) in 2010 and 7% (B7) in 2011.

**** Sum of hydraulic infrastructure tax, liquid fuels and natural gas tax and minimum assumed income tax. Biodiesel production for the domestic market is exempted from these taxes.

***** Biodiesel export tax (20%) minus value-added tax (2.5%).

****** 35% in 2010, 50% in 2017 and 60% in 2018.

The policy framework for the biodiesel industry differs among market destinations. Biodiesel production for the domestic market is supported with a subsidy (tax exemptions), a *cost-plus* biodiesel pricing policy, a supply quota scheme supporting *s&m* firms and a biodiesel mandate with increasing blending targets (SyCDNA 2006; SE 2010a, b). The biodiesel export market is regulated with an export tax on biodiesel and additional taxes from which biodiesel producers supplying the domestic market are exempted. Environmental constraints apply to biodiesel export, requiring a specific level of GES imposed in the EU-RED (EC 2009).

The fossil fuel sector is regulated through different policy instruments applied to the fuel domestic demand and diesel imports, accounting for the maximum fuel price policy and the tariff on fossil diesel imports. The soybean sector is regulated by an *ad-valorem* DET, with taxes decreasing as the value-added of the product increases (MEyP 2008).

6.3. Scenario of external factors evolution

Given the interrelation between international price and demand and their dependency on international market dynamics, plausible scenarios of market evolution should prove coherent between variables interaction. To this end, a single set of price-demand projections is defined based on Agricultural Outlooks to account for the evolution of external factors over time and their interrelation. The advantage of using agricultural outlook projections assures a coherent framework that accounts for complex dynamics in the international market.

Scenario variables include mainly international demand, price and yield projections for soybean and value-added products, pastures and competing crops. Table 6-3 shows the initial values and the compound annual growth rate of scenario variables. This approach has the advantage that alternative scenarios can be generated in the simulation model.

Table 6-3. Scenario variables evolution.

Scenario variable	**Initial value 2001**	**Value 2010**	**r(2001,2010)**	**Final value 2025**	**r(2010,2025)**
International demand	**Ktons/year**	**Ktons/year**	**%**	**Ktons/year**	**%**
Soybean	6'984	13'000	6.4%	16'267	2.3%
Oil	3'080	4'277	3.3%	7'919	6.4%
Meal	13'725	24'698	6.1%	39'705	4.9%
Biodiesel		1'144	21.5%	1'384	1.9%
Diesel fuel ***	8530	10445	2.0%	12499	1.8%
Meat****	2'880	3'375	1.6%	3'053	-1.0%
Corn****	16'120	22'992	3.6%	23'302	0.1%
International price	**US$/ton**	**US$/ton**	**%**	**US$/ton**	**%**
Soybean	200	429	7.9%	472	1.0%
Oil	336	924	10.6%	1'361	3.9%
Meal	188	391	7.6%	349	-1.1%
Diesel	28.3	59.4	7.7%	94.2[**]	4.7%
Biodiesel	NA[*]	1'188	2.2%	1'768	4.1%
Meat	292	880	11.7%	1798	7.4%
Corn	89	163	6.2%	199	2.0%
Yield	**ton/ha/year**	**ton/ha/year**	**%**	**ton/ha/year**	**%**
Soybean	2.67	2.93	0.9%	3.18	0.8%
Pasture	0.31	0.49	4.7%	0.56	1.2%
Corn	5.45	8.33	4.3%	8.29	0.0%

[*] r calculated based on 2005 value (first year of biodiesel production in Argentina)
[**] r calculated based on 2020 value (last year of FAO projection)
[***] domestic demand
[***] total demand

Scenario variables values are estimated based on the market analysis of each sector. Appendix 9.5 describes the main market evolution assumptions concerning the Argentinean case. For each product, trends in the international demand and price are given by projections (2010-2025) of the FAPRI 2011 Agricultural Outlook (FAPRI 2010b). Trends in the diesel international price and the fuel domestic demand are based on projections (2010-2020) of the FAO-OECD 2010 Agricultural Outlook (OECD-FAO 2010). For the period 2001-2010 the historical values are used in the model.

6.4. Biodiesel production, markets and firms allocation

The first step in the assessment of the biodiesel export potential is the evaluation of the effect of the policy framework on the quantity of biodiesel supplied to the export market. The next section presents simulation results to assess the effect of the blending target, the domestic biodiesel price policy, the supply quota scheme, and the export tax regime on the quantity of biodiesel supply to each market by each producer type.

6.4.1. Effect of domestic blending target

Biodiesel domestic demand partially depends on the domestic biodiesel blending target level (Figure 6-1). In the REF case, the blending target is set at 5% in 2010 (B5) and 7% (B7) in 2011, generating a biodiesel domestic demand of 714 kton/year in 2011, increasing to 896 kton/year by the end of the simulation period, given the increased demand for fuel by final consumers. Obviously, increasing the blending target to B10 increases biodiesel domestic demand, provided that refineries are obliged to blend biodiesel in the domestic market. In this case, the B10 implementation in 2012 increases biodiesel demand to 1028 kton/year (1282 kton/year by 2025).

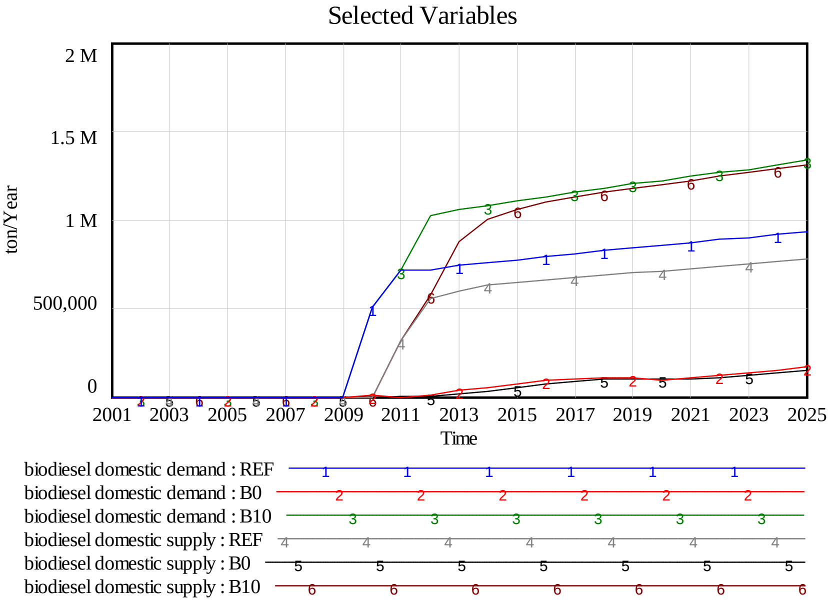

Figure 6-1. Biodiesel domestic demand: Effect of blending target level.

On the other hand, simulations show that if no blending target is implemented (B0) in Argentina biodiesel domestic demand reaches 0.3 Mton/year at the end of the simulation period. This low biodiesel demand may be explained by the fact that the diesel price to the blender is lower than the biodiesel domestic producer price. Consequently, the mandate implementation sets a fixed biodiesel domestic demand that induces biodiesel supply to the domestic market.

Concerning biodiesel exports, simulations show that increasing blending targets seems to decrease the biodiesel export potential. Figure 6-3 depicts the effect of the domestic biodiesel mandate on biodiesel export supply for different blending target levels.

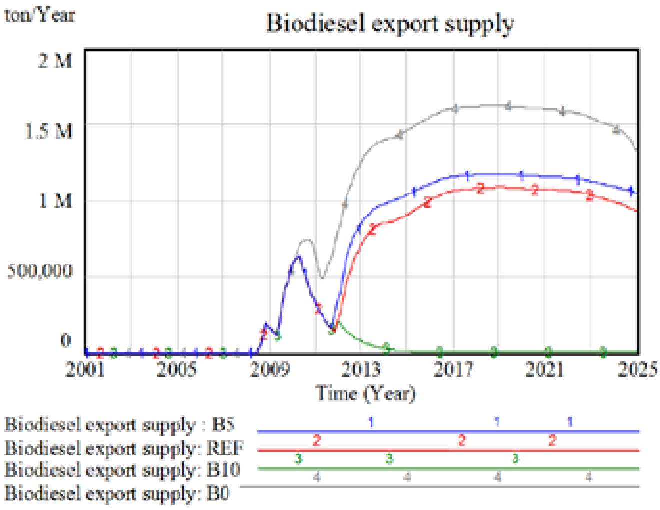

Figure 6-2. Biodiesel export supply: Effect of blending target level.

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In the first case, where no blending target is implemented (B0) in Argentina, biodiesel production is almost completely diverted to the export market. In this case, biodiesel exports sum up to 1.5 Mton/year while biodiesel supplied to the domestic market is only 0.18 Mton/year, at the end of the simulation period. Biodiesel exports are reduced when the B7 (REF) and B5 blending targets are implemented. The interesting result however is that increasing the biodiesel domestic blending target to B10 seems to reduce biodiesel exports to zero.

The implications of the Argentinean biodiesel blending target on the biodiesel export potential seem to be linked to its effect on the biodiesel production costs. In the REF case with a B7 blending target, biodiesel production costs are 1200 and 1056 US$/ton for *s&m* and large firms respectively. Simulation results indicate that increasing blending targets increase biodiesel production costs (Table 6-4). For instance, if a B10 blending target is implemented, biodiesel production costs will increase to 1231 and 1126 US$/ton for *s&m* and large firms respectively. Provided that other costs are assumed constant, this result is explained by the effect of the blending target on the international price of soybean oil.

Table 6-4. Effect of blending target level on producer profits and biodiesel exports.

Variables in 2025	**Units**	**REF (B7)**	**B0**	**B5**	**B10**
Biodiesel production costs	US$/ton				
Large firm		1056	991	1028	1126
Small and medium firm		1200	1149	1180	1231
Biodiesel for export unit profit	US$/ton				
Large firm		37	151	84	0
Small and medium firm		0	0	0	0
Biodiesel supply	kton/year	1729	1508	1608	1312
Biodiesel domestic supply	kton/year	796	183	558	1312
		46%	12%	35%	100%
Biodiesel export supply	kton/year	932	1325	1050	0
		54%	88%	65%	0%

Simulations show that the AR blending mandate increases the international soybean oil price. While the effect is still marginal for the simulated blending target levels, it seems to be enough to drive the producer export unit profit to zero. In the simulation experiment, increasing the blending target to B10 results in a 5% increases in the international soybean oil price above the REF case. This price increment seems to increase biodiesel production costs above the revenue level large forms get from supplying the international market, driving biodiesel profits from the export market to zero (Table 6-4). On the other hand, given that the domestic biodiesel price is regulated by the *cost-plus* pricing policy, increasing the soybean oil international price will increase the biodiesel domestic price and consequently biodiesel supply to the domestic market.

In conclusion, increasing blending targets increase biodiesel domestic supply and reduce the AR biodiesel export potential, at least for the blending target levels tested in the simulation.

6.4.2. Effect of biodiesel domestic price policy, supply quotas and export tax

On the supply side, the biodiesel export potential by each producer type depends mainly on the production level and accompanying instruments of the biodiesel policy. The production level depends on the aggregated unit profit of each biodiesel producer type. Producer profits are mainly affected by the biodiesel *cost-plus* pricing policy, the biodiesel international price, the biodiesel export tax applied and the production costs. Additionally, supply quotas regulate the amount of biodiesel supplied by each producer type in the domestic market also influencing the biodiesel export potential.

Figure 6-3 shows the effect of policy instruments on biodiesel supply to the international market. Table 6-5 shows simulation results for the effect of policy instruments on biodiesel producers' unit profits and its effect on the export potential by 2025.

Simulations show that, compared to the REF case, AR biodiesel exports seem to be mainly affected by the export tax regime. Indeed, in the SOT case, increasing the soybean oil export tax by 10% almost doubles biodiesel exports. Alternatively, increasing the biodiesel export tax by 10% as in the BT case, reduce AR biodiesel export to zero. This result is not surprising, provided that export taxes affect directly biodiesel producer profits.

The effect of the biodiesel domestic price policy, on the other hand, appears to be more complex as it has different implications for large and *s&m* firms. In the REF case, the biodiesel *cost-plus* pricing policy sets the domestic biodiesel price higher than the price of biodiesel diverted to the export market (1228 and 1094 US$/ton, respectively, by 2025). This occurs because the domestic biodiesel price adjusts to the change in the soybean oil international price and the biodiesel international price adjusts to the balance of biodiesel supply and demand in the international market. In the REF case, simulations show that the domestic unit profit of *s&m* firms is higher than the profit they receive from the export market (Table 6-5). Provided that the domestic *cost-plus* pricing policy adjust to changes in production costs, the policy sets a constant domestic biodiesel unit profit equal to 28 US$/ton. The biodiesel export unit profit of *s&m* firms on the other hand is 0 US$/ton provided that at this international biodiesel price level, *s&m* firms can not cover their production costs. This situation may motivate their decision to supply the domestic market.

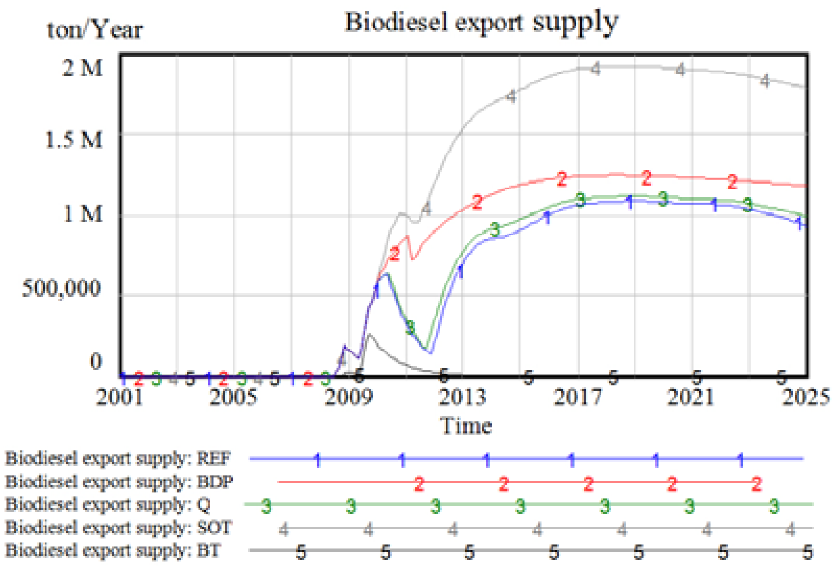

Figure 6-3. Biodiesel supply to the international market: Effect of policy instruments.

The domestic biodiesel unit profit level however, applies to *s&m* firms provided that the cost structure of the *s&m* firm is assumed to be used in the biodiesel domestic price formation. Large firms supplying the domestic market can get additional profits provided that their production costs are lower. Simulations show that in the REF case large firms domestic unit profit is 37 US$/ton by 2025, compared with the constant 28 US$/ton for *s&m* firms. Moreover, given the higher domestic biodiesel price, large firms gets higher unit profits if supplying the domestic market than if they supply the international market (172 and 37 US$/ton, respectively). Case BDP shows that removing the biodiesel domestic price control policy may therefore leave *s&m* firms out of the market as they cannot compete with large firms in the domestic nor in the international market given the difference in production costs. On the other hand, the ability of large firms to supply the domestic market is constrained by the supply quota policy.

Case Q shows the implications of the domestic supply quota. The supply quota scheme allows *s&m* producers to supply the domestic market, allocating the remaining domestic demand to large producers (Table 6-5). Given that large producers have lower production costs than *s&m* producers, removing the quota will allow large firms to increase their supply to the more profitable domestic market. Without the biodiesel supply quota, *s&m* firms lose market share in the domestic market (92% and 0%, respectively for the REF and Q cases). The cost of biodiesel production for the domestic market, without the supply quota therefore is reduced. Moreover, simulations show that removing the supply quota scheme will reduce both biodiesel production and the quantity of biodiesel supplied to the domestic market. This occurs probably because *s&m* firms are left out of the market and large firms which supply the domestic market increase the biodiesel international price. In this context, given that the biodiesel domestic unit profit is fixed by the government large firms gain higher unit profits by exporting the biodiesel.

However, case SOT shows that biodiesel exports by *s&m* firms may be possible. In this case, increasing the oil export tax by 10% will increase the biodiesel export unit profit of *s&m* firms to 167 US$/ton by 2025. This is due to the fact that the soybean oil export tax affects directly the biodiesel production costs. Simulations show that an increment in the soybean oil export tax by 10% reduces the soybean oil producer price from 825 to 714 US$/ton. This price reduction allows biodiesel producers to reduce costs, increasing biodiesel supply with respect to the REF case from 1729 kton/year to 2304 kton/year. Large firms, on the other hand, also benefit from the tax increment, allowing to increase unit profits from both markets (154 US$/ton and 293 US$/ton respectively). Consequently, an increment in the soybean oil export tax increases supply of biodiesel to both markets.

Table 6-5. Effect of policy instruments in the biodiesel sector.

Variables in 2025	**Units**	**REF**	**BDP**	**Q**	**SOT**	**BT**
Biodiesel supply	kton/year	1729	1946	1381	2304	918
Biodiesel domestic supply	%	46%	39%	28%	22%	100%
Large firm		8%	4%	100%	1%	20%
Small and medium firm		92%	96%	0%	99%	80%
Biodiesel export supply	%	54%	61%	72%	78%	0%
Large firm		100%	100%	100%	76%	0%
Small and medium firm		0%	0%	0%	24%	0%
Biodiesel domestic producer price	US$/ton	1228	1159	1228	1092	1228
Biodiesel export producer price	US$/ton	1094	1159	1094	1232	938
Biodiesel production costs	US$/ton					
Large firm		1056	1051	1022	938	1098
Small and medium firm		1200	1200	1200	1064	1200
Biodiesel domestic unit profit	US$/ton					
Large firm		172	108	206	154	130
Small and medium firm		28	0	28	28	28
Biodiesel for export unit profit	US$/ton					
Large firm		37	108	71	293	0
Small and medium firm		0	0	0	167	0

Beside the effect of the soybean oil export tax on production costs, biodiesel producer profits are affected by the *ad-valorem* tax on biodiesel exports. In the REF case the effective tax level is 17.5%, given the 2.5% VAT reimbursement policy. Case BT shows that a 10% increment in the biodiesel export tax reduces the biodiesel producer price for the international market from 1094 US$/ton to 938 US$/ton compared with the REF case. The result is a reduction on biodiesel supply and the suppression of biodiesel exports. At this tax level, biodiesel producers' unit profits drop to zero, given the projected evolution of the biodiesel international price and the production costs.

The effect of the biodiesel export tax however, differs among producer types given the different cost structures of each producer. The large firm export unit profit is reduced below the domestic unit profit level when the export tax for instance, is increased by 5%. Therefore, a tax increment on biodiesel exports will motivate large companies to supply the domestic market, at least at this tax level. *S&m* firms, on the other hand are left out of the international market if the biodiesel export tax is also increased by 5%. Due to their higher production costs, a 5% increment in the biodiesel export tax still drops the *s&m* firm export unit profit to zero.

As expected, simulation results in Table 6-5 shows that large firms are mainly export oriented and *s&m* firms supply the domestic market. Apart from the supply quota policy that constrains large firms' supply to the domestic market and the lower production costs, large firms are owned by large crushers that are typically oriented to the international market

(CADER 2011). These different characteristics among producer types can also explain producers' decision about the biodiesel market to be supplied. In the REF case, simulation results show that by 2025 supply to the domestic market by the large and *s&m* firm are 62 kton/year and 735 kton/year, respectively. Biodiesel supply for the international market, on the other hand, is completely dominated by large firms, supplying 932 kton/year by 2025.

6.5. Land supply for soybean production

Soybean land supply derives mainly from market dynamics in the crushing sector. The effect of biodiesel production in this context depends on how the additional oil demand for biodiesel will impact soybean producer profits that will, in turn, influence land allocation for soybean production. A first step in this analysis implies determining the effect of biodiesel demand on soybean land supply. Simulations are therefore performed to assess the effect of policy instruments and international market dynamics on soybean land supply.

6.5.1. Effect of domestic policy instruments

In the REF case, soybean land increases from 12.71 Mha in 2001 to 26.36 Mha in 2025, given the projected trend in the international prices for soybean, oil, meal and biodiesel (Figure 6-4). The simulated biodiesel demand levels, however seem to have little impact on land supply for soybean production. Cases B0 and B10 show that while the blending mandate may increase soybean oil international price, this price increment is expected to be marginal. Indeed, in the simulation experiment, the B10 blending target increases the international price of soybean oil by 5% by 2025 (Table 6-6).

On the other hand, if no biodiesel domestic mandate is in place (B0), the soybean oil international price is also reduced by 5%. As showed in Table 6-4, this price increment can have important implications in the biodiesel sector, reducing the biodiesel export potential to zero. However, in the crushing sector, its effect seems to be marginal given the still low share of biodiesel on soybean oil demand. Consequently, the relative contribution of biodiesel production to soybean land supply is expected to remain small. Other drivers of soybean demand seem to have a significantly higher impact that the blending target on soybean land expansion.

On the other hand, the effect of export taxes can have several implications on soybean land expansion. Table 6-6 shows that at the end of the simulation period, soybean oil exports are reduced if the soybean export tax is increased (ST case). The soybean export tax seems to be the key policy instrument regulating soybean land supply (Figure 6-4). Increasing the soybean export tax by 10% may increase the international soybean oil price by 30%, given the reduction in soybean land unit profit that discourage agricultural producers to plant soybeans. This is a plausible case provided that in 2008 the government increased the soybean export tax by implementing a moving tax scheme that adjusted the soybean export tax based on the change in the soybean FOB[41] price (MEyP 2008). Due to the increment in the soybean international price, the application of this policy resulted in an increment of the soybean tax to 45%. The effect of such an increment on the soybean export tax may generate a 23% reduction in soybean land supply. This result however, is subjected to the prices, yield and

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[41] Free on board.

costs evolution of alternative land-uses. For instance, projections indicate that corn land unit profit will remain stable, while soybean land unit profit is projected to increase (Table 6-3). This evolution trends consequently seems to indicate that land diverted to soybean may increase. Reducing the corn export tax from the current 25% therefore may change land allocation patterns among competing crops.

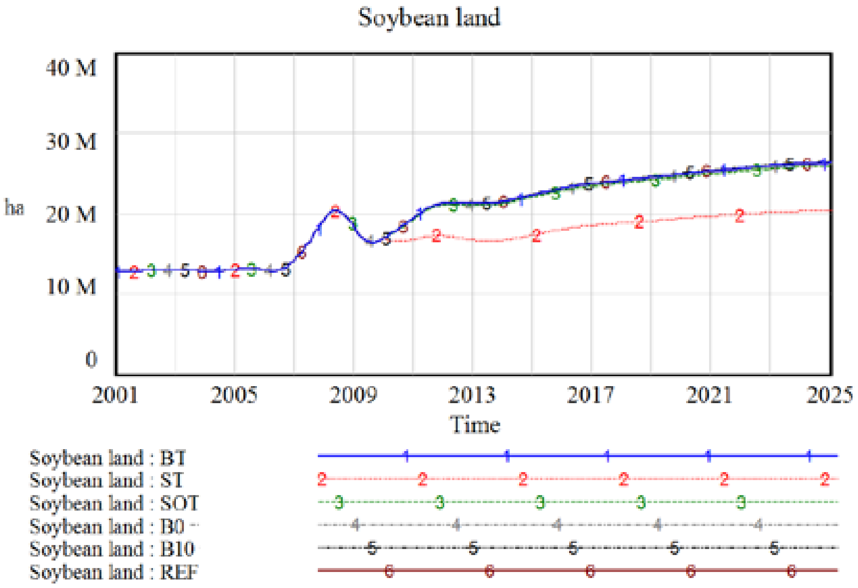

Figure 6-4. Soybean land: Effect of domestic policy instruments.

Table 6-6. Effect of policy instruments in the crushing sector.

Variables in 2025	Units	REF	ST	SOT	BT	B0	B10
Meal international price	US$/ton	334	28%	1%	0%	0%	0%
Oil international price	US$/ton	1214	30%	1%	0%	-5%	5%
Soybean international price	US$/ton	437	6%	-1%	0%	0%	0%
Soybean crush margin	US$/ton	46	272%	-34%	0%	-13%	8%
Soybean land profit	US$/ha	126	-16%	-1%	0%	0%	0%
Meal supply	Mton/year	53.92	-28%	-2%	0%	-1%	0%
Oil export supply	Mton/year	12.13	-28%	-2%	0%	-1%	0%
Oil supply for biodiesel	Mton/year	1.55	-47%	33%	-47%	-13%	-24%
Soybean supply	Mton/year	83.68	-23%	-1%	0%	-1%	0%
Soybean land	Mha/year	26.36	-23%	-1%	0%	0%	0%

Export taxes however, seems to be the main policy instruments affecting the crushing industry. Indeed, in the ST case, the aggregated soybean crusher increases its crush margin by 272% when the soybean export tax is increased by 10%. Moreover, export taxes affect also soybean oil supply for biodiesel. For example, in the SOT case increasing the soybean oil export tax by 10% increases oil supply for biodiesel by 33%. On the other hand, the BT case shows that increasing the biodiesel export tax by 10% reduces oil supply for biodiesel by 47%. In conclusion, the export tax regime seems to significantly influence the biodiesel export potential, provided that soybean oil supply for biodiesel is significantly affected by the export tax level, at least for the cases assumed in the simulation experiments.

In contrast, soybean land unit profit seems to be less affected by the domestic blending mandate. For instance, soybean land profit remains nearly constant independently of the biodiesel blending target level. This result may be explained by the fact that despite the international soybean oil price increases, which may increase soybean demand for crush, projections indicate that the soybean international price is expected to remain stable at current levels (Table 6-3). Moreover, Argentina has a relatively small market share in the soybean international market, and therefore it is expected not to influence the international soybean price. Consequently, soybean producers seem not to perceive any additional incentive to increase soybean land due to soybean demand for biodiesel production.

6.5.2. Effect of international market dynamics

Besides the effect of domestic policy instruments, land supply for soybean production depends also on international market dynamics for soybean value-added products. Table 6-3 shows that international demand for AR soybean oil and meal are projected to increase more than the international demand for AR biodiesel. Soybean land supply for biodiesel therefore is also expected to be less significant over time (Figure 6-5). For instance, simulations show that if no mandate is implemented (B0 case) in Argentina, land supply for biodiesel production accounts for 14% of soybean land supply for soybean oil production. Moreover, biodiesel contribution to soybean land supply is expected to decrease over time given the increased soybean land supply for soybean oil and meal exports. Land supply for soybean production seems to be mainly influenced by the international soybean meal price, given the significant share of meal on the value of soybean crush.

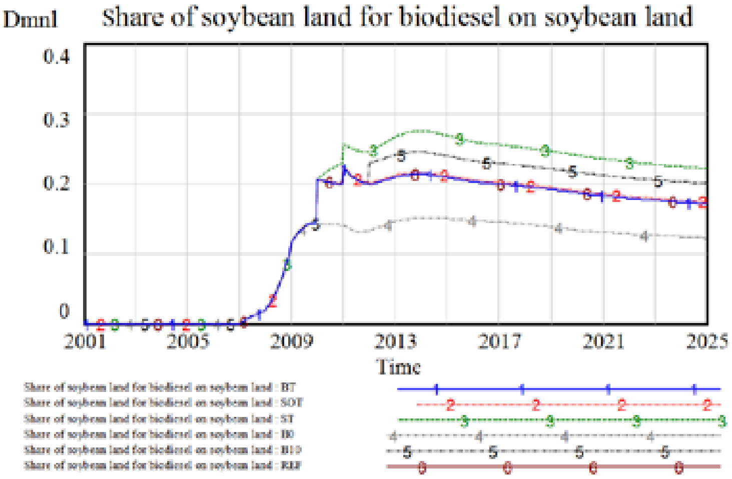

Figure 6-5. Share of soybean land for biodiesel.

The implications of meal market dynamics on land supply for soybean production are complex. A first issue to be considered is the joint product relation in soybean crushing. Soybean oil is a dependent co-product, given the joint product relation and the value-added of soybean meal as main driver of soybean crush. Consequently, considering that Argentina is the first soybean meal world exporter, land supply for soybean production depends mainly on the evolution of the soybean meal international market.

The REF case shows that Argentinean meal exports are expected to increase mainly due to increased demand for animal feedstock in the European Union (Table 6-3). On the other hand, the meal international price is expected to remain constant. In this case, within certain limits, an increase in the international price for soybean oil will not lead to a significant increase in land supplied for soybean production. For instance, cases B0 and B10 show that meal supply to the international market and land supply for soybean production remain unchanged, independently of the blending target level. Moreover, simulations show that the domestic mandate implementation has no effect on the international meal price (Table 6-6), giving evidence of the different demand drivers for soybean oil and meal.

Simulation results however, reveal that the relative increment in soybean oil price will be higher than the relative increment in meal price (Table 6-3). Therefore, provided that the value of oil production increases more than the value of meal production, soybean oil supply is expected to increase its contribution to the soybean crush margin and consequently its effect as a driver of soybean land supply.

In the REF case, AR meal supply to the international market remains unchanged independently of the level of biodiesel production. This conclusion has important implications for assessing iLUC. Provided that soybean meal is a good substitute for corn (and other meals) as animal feedstock, if biodiesel production induced a surplus production of meal, the increased meal supply may therefore reduce corn land demand reducing land-use changes induced by biodiesel production. However, this seems not to be the case, provided that biodiesel production appears not to be affecting the international soybean meal price. Moreover, due to the co-product dependency, some authors argue that it is not appropriate to consider a potential surplus of soybean meal as an iLUC credits for biodiesel (Bauen *et al.* 2010). Nonetheless, assessing iLUC impacts of co-products surplus also requires a global modeling approach because of trade interaction in the animal feedstock sectors among producing countries (Taheripour *et al.* 2008).

Concerning soybean oil market dynamics, the effect of biodiesel production on soybean oil exports is important because it affect the relative contribution of biodiesel production on LUC at the country level. Soybean oil is considered in this analysis as a dependent co-product. Consequently, market effects of biodiesel production have limited influence on land supply for soybean production. Moreover, the effect of the international soybean oil demand is important in the Argentinean case, because the country is the first soybean oil world exporter. Some authors argued that the development of the AR domestic biodiesel industry responds mainly to a surplus of soybean oil when there has been no market for this product (CADER 2011). In this case, diversion of soybean oil to the biodiesel market does not necessarily imply a reduction in soybean oil for food markets. This effect is important when assessing indirect land-use changes (iLUC).

The effect of soybean-based biodiesel production on iLUC has been addressed by several authors (Searchinger and Heimlich 2008; Bauen *et al.* 2010; Edwards *et al.* 2010b). While estimates of iLUC (and its related GHG emissions) considerably vary in the literature, some common pathways link modeling approaches. In the case of soybean-based biodiesel, the rationale behind the estimation of the iLUC is that domestic biodiesel production may divert soybean oil for food (and other uses) in the international market to the fuel use in the domestic market. In this case, additional land may be diverted to soybean production in order to replace soybean oil use for fuel that was diverted from the food market. Estimates varies mainly depending on the assumption made concerning the demand for soybean oil for non-fuel use, the soybean yield, the type and source of oil used to replace soybean oil in the markets from where it is diverted and the production patterns in soybean and other vegetable oil producing countries (Searchinger and Heimlich 2008).

Following this analysis, the reduction in Argentinean soybean oil exports may induce an increment in vegetable oil supply in other countries. Soybean oil may be supplied by other soybean producing countries or replaced by other vegetable oil type in other countries. For instance, soybean oil can also be produced mainly in Brazil, US, India and China. Soybean substitution by rapeseed oil is not likely to occur given that production is mainly concentrated in the EU, which is expected to reserve rapeseed oil for domestic biodiesel and food use. The main substitute of soybean oil in the international market is palm oil. Palm oil producers, mainly Malaysia and Indonesia, may also supply the displaced soybean oil (Croezen 2010). The resulting indirect land-use change for the relocation of soybean oil will depend mainly on land-use patterns in the producing country and on the quantity of soybean oil to be replaced (Bauen *et al.* 2010). However, assessing this effect implies accounting for global trade interaction of oilseed commodities in a worldwide scale. Therefore a complementary approach should be applied to account for the implications of Argentinean biodiesel production on iLUC at the global level.

6.6. Land-use change from soybean production

The biodiesel GES depends mainly on LUC GHG emissions. Simulation results in sections 6.4. and 6.5. showed that the impact of biodiesel production in Argentina has a marginal effect of land requirements for soybean production. Land requirements however can change among locations depending on land productivity and the cultivation method. The resulting LUC moreover, depends also on land expansion patterns. Critical issues affecting LUC in this analysis are the soybean yield, the competition for land among managed land uses and the expansion patterns of cropland into unmanaged lands. The following sections therefore, build on simulation results to analyse these issues for the four soybean supply regions.

6.6.1. Effect of land productivity and cultivation methods

In the simulation model, land productivity and the share of soybean cultivation methods determine the soybean yield in each region. The additional amount of land required for soybean production depends on the soybean yield evolution (Figure 6-6). Among supply region different land productivities exist and different soybean cultivation methods are applied, resulting in different soybean yields. Additionally, given the projected trend (Table 6-3) soybean yields increases over time, independently of the soybean supply region.

The C region is the most productive one and where first occupation no-tillage (FONT) farming is most widespread among soybean producers. This results on the highest soybean yield in the country (3.4 ton/ha.year by 2025). In other regions yields are considerably lower given lower land productivities and the application of conventional tillage and second soybean cultivation. Average soybean yields are 2.7, 2.5, 2.4 ton/ha.year in the SE, NE, and NO regions, respectively. Moreover, the reduction in land productivity given the expansion of managed lands into “assumed” less productive lands is higher in soybean region that require more soybean land. Consequently, land requirements are highest in the NO and lower in the C region. Obviously, these factors affect land profits of soybean producers.

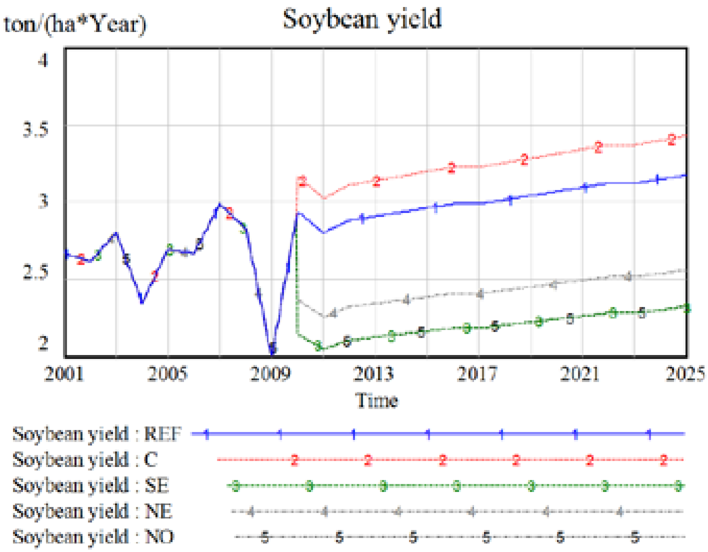

Figure 6-6. Soybean yield by region.

In summary, the assumed yield improvement trend for the soybean yield seems to overpass the land productivity loss from cropland expansion. Provided that the expected yield influences unit land profits of soybean producers, changing this assumption can significantly affect the quantity of land diverted to soybean production.

6.6.2. Effect of managed land competition

Managed land competition depends on relative unit land profits among competing managed land-uses. Unit land profits of each managed land-use vary between regions resulting on different land expansion patterns (Table 6-7). Simulation results indicate that soybean land increases mainly in the C region. Soybean production seems to be more profitable in the C region compared with other crops and pasture production. If production patterns in the C region are assumed (case C), soybean land will increase by 8.5 Mha and other crops and pastures will be reduced by 1.2 Mha and 3.5 Mha, respectively. In the rest of the regions, soybean land supply is lower compared with the C region given lower soybean yields in these regions that results in lower soybean land unit profits.

Besides managed land competition, land allocated to each managed land type seems to be related to the possibility of expansion of managed land in each region. In the C region, for instance, land is primarily under agricultural use and so managed land expansion possibilities are lower than in other regions. Consequently, competition between managed lands is higher in this region that results in a reduction of other crops and pastures. For instance, in the C case managed land increases only by 4.25 Mha over the simulation period. On the other hand, in the NE case managed land increases by 36.24 Mha, mostly for pasture (beef) production. Consequently, soybean, other crops and pasture land increase given the higher possibility of cropland and pasture lands to expand into unmanaged lands. The same seems to occur for the SE and NO regions (Table 6-7).

The type and share of converted unmanaged lands differs among regions which result on different cropland expansion patterns (Figure 6-7). If soybean production moves to the NO region then, the main converted land-uses are grassland (2.4 Mha) mixedland (1.3 Mha) and savannas (1.3 Mha). Note that the highest expansion into forestland occurs in both northern regions; obviously these are the areas with the highest forest cover. High carbon stocks are associated with these types of land-use. Therefore, expansion into the NO and the NE region will also reduce the GES of the biofuel, if current land-use change patterns continue in the future.

Table 6-7. Cumulative change in land by land-use type.

Cumulative change		C	SE	NE	NO
Soybean land	Mha	8.82	8.08	7.19	5.63
Other cropland	Mha	-1.22	2.73	5.13	2.52
Pasture	Mha	-3.52	10.19	21.29	4.94
Managed land	Mha	4.25	22.61	36.24	13.97

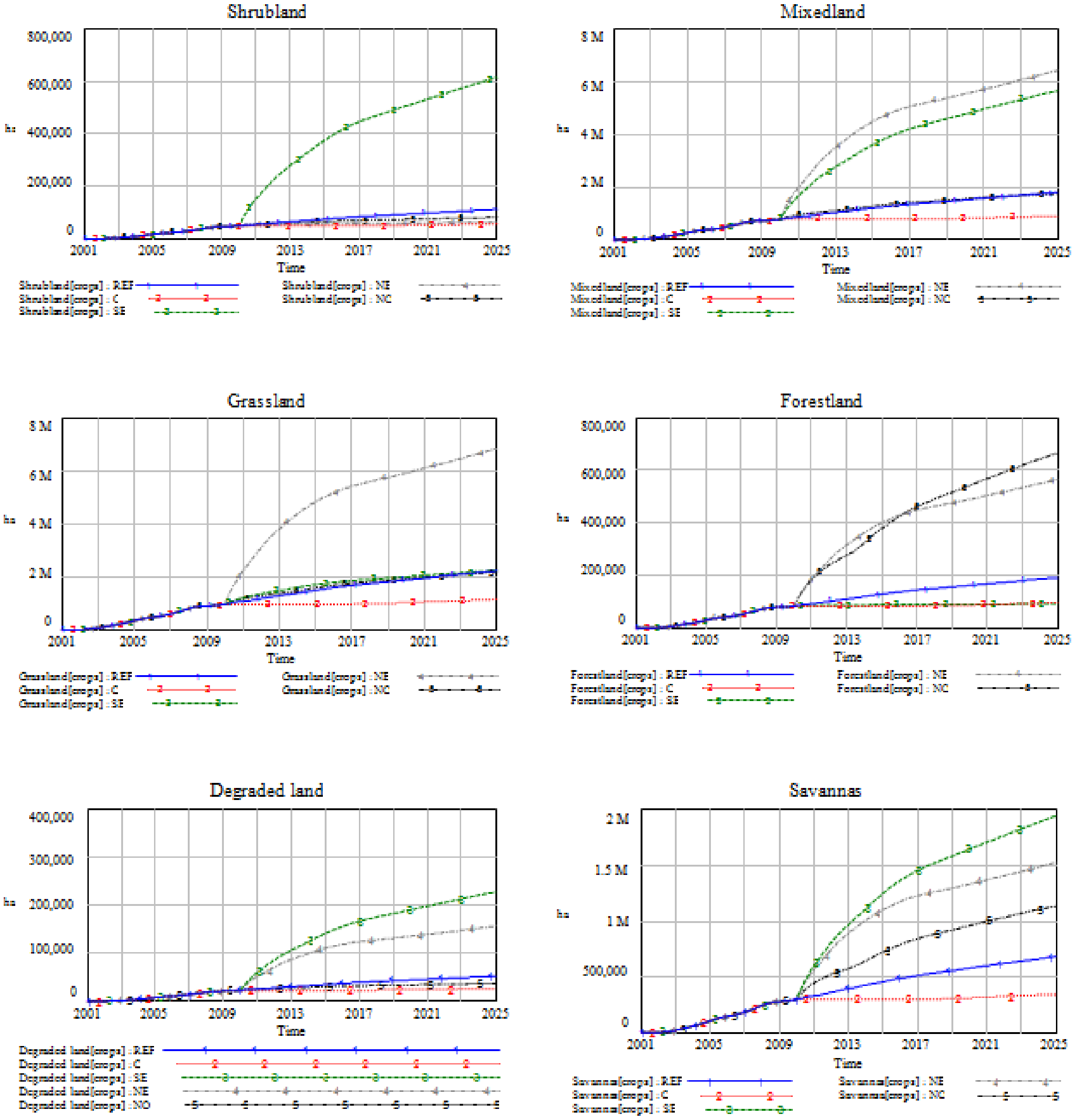

Figure 6-7. Cropland expansion into unmanaged land by supply region.

Finally, if soybean production moves to the SE region, the main converted unmanaged land-uses are mixedland (6.6 Mha), grassland (2.4 Mha) and savannas (2.3 Mha). Significant potential however, seems to be available for managed lands expansion into degraded lands in the NE and SE regions. While current expansion patterns are low, probably because of low land profits in these lands, these patterns can change if policy instruments are implemented to increase the attractiveness of crops cultivation in degraded lands. From an environmental perspective, expanding the agricultural frontier into the SE region may avoid expansion into forest land in the NO and increase carbon stocks if agricultural expansion is diverted toward degraded lands.

Note that unmanaged land availability is constrained in the C region while other regions have a higher potential for cropland and pasture expansion. This limitation may explain the fact that the agricultural frontier is moving into other regions not only for soybean production but also for the relocation of other crops and pastures being displaced from the C region. These results seem to suggest that reducing the impact of soybean expansion on land-use change then, may imply the design of additional policy instruments in order to change current managed lands expansion patterns[42]. These instruments can prevent deforestation and increase the attractiveness for cultivation into degraded lands. The potential key regions for redirecting soybean cultivation may be then the NE and SE regions.

6.7. Biodiesel exports under the GHG emission saving threshold

The most significant part of GHG emissions are generated during soybean production, including emissions from soybean cultivation and LUC emissions (Panichelli *et al.* 2009). Simulations then are used to assess the effect of land-use change patterns and soybean cultivation methods on the GHG emissions balance of the biofuel.

Once the biodiesel GES is determined, simulations are performed to account for the effect of the threshold imposed in the EU-RED. To this end, simulations compare the GES for different soybean supply cases and assess the quantity of biodiesel that can be potentially exported depending on the region from where soybean is supplied.

6.7.1. Biodiesel life cycle GHG emissions and emission savings

Figure 6-8 shows the biodiesel GHG emission balance in gCO2eq/MJ. The left hand side figure shows the emission balance without including LUC GHG emissions. In this case, soybean production emissions largely vary across regions given the different inputs used in each soybean cultivation method and the different share of methods in each region. First occupation no-tillage (FONT) farming is the method that results in the lowest GHG emissions (36 gCO2eq/MJ), being the C region where this method is most widely applied. Highest emissions result in the SE region (44 gCO2eq/MJ), under second occupation no-tillage farming, due to the low yields obtained in this region.

Annualised GHG emissions from dLUC, on the other hand, depend mainly on the type of unmanaged land-use displaced in each region and the biodiesel supply level. In the REF case, annualised dLUC GHG emissions of soybean-based biodiesel are 13 gCO2eq/MJ (Figure

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[42] Policies directed to improve yields or develop alternative feedstocks are also relevant.

6-8). Given the lower land requirements and the type of unmanaged land-uses displaced, producing biodiesel in the C region generate the lowest dLUC GHG emissions (10 gCO2eq/MJ). On the other hand, if soybean production for biodiesel expands in the NO region, it will result on the highest emissions from dLUC (46 gCO2eq/MJ).

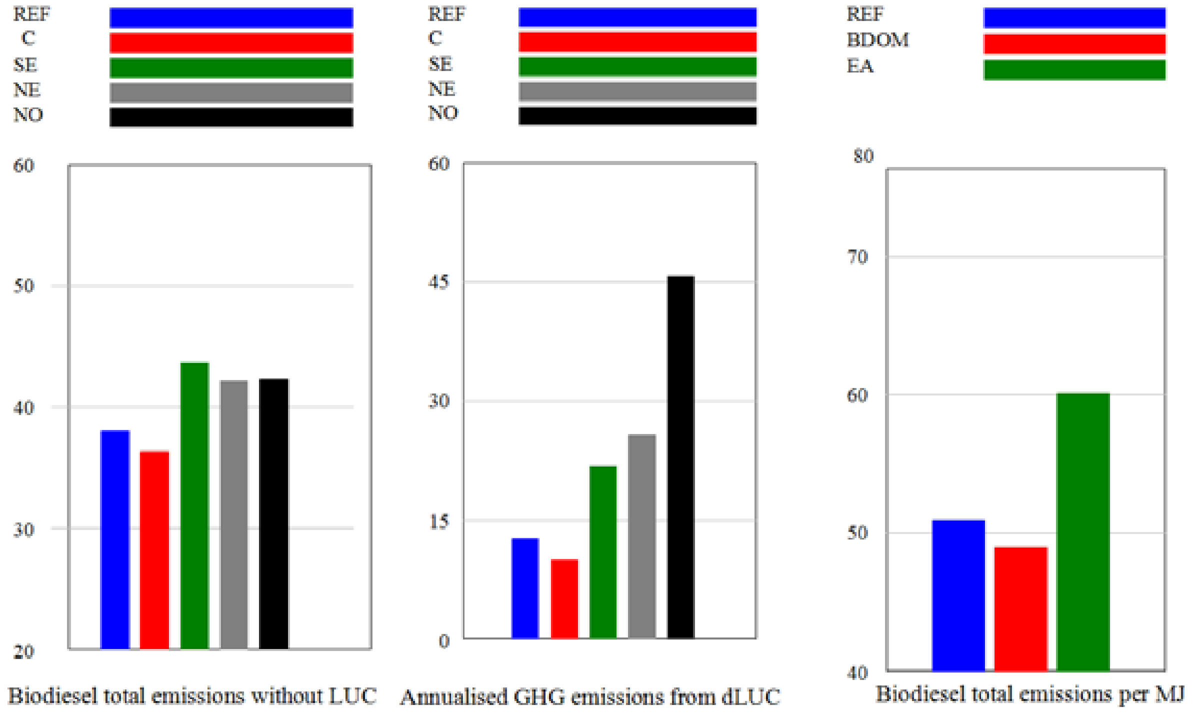

Figure 6-8. GHG emissions by supply region.

Biodiesel production emissions vary also depending on the biodiesel market destination and the allocation method. In the REF case, where biodiesel total emissions are estimated for the export market and allocated based on the energy content of each co-product, total biodiesel emissions sum up to 51 gCO2eq/MJ. On the other hand, case BDOM shows that producing biodiesel for the domestic market results in lower emissions, due to the avoided transoceanic transport (49 gCO2eq/MJ). However, higher differences are obtained if economic allocation is used (EA case), compared to the energy allocation choice in the REF case (60 gCO2eq/MJ for biodiesel supplied to the export market). Shifting to an economic allocation method therefore will increase the GES of the biofuel by transferring emissions from co-products (meal and glycerine for the oil extraction and transesterification unit processes) to biodiesel.

The GES of the biodiesel at the end of the simulation period is given in Figure 6-9.

The REF case shows that the GES of AR soybean-based biodiesel is 39%. Moving soybean production for biodiesel to the C region will increase the GES to 44%, increasing the export opportunities of Argentinean biodiesel producers. Firms located in the SE and NE regions have a positive GHG emission balance (GES=21% and 18%, respectively). Nevertheless, while they generate environmental benefits in terms of GES, they are not able to export given the fact that they do not comply with the EU-RED GES threshold.

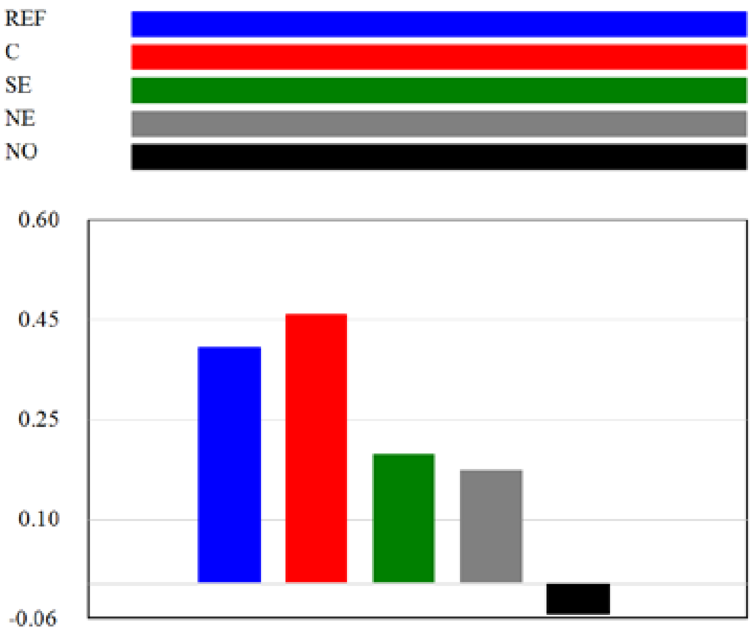

Figure 6-9. Emissions reduction potential by soybean supply region.

Finally, producers located in the NO region have negative GES due to GHG emissions from dLUC (GES= -5%). This means that producing biodiesel in this region leads to higher GHG emissions that the emission saving generated by substituting diesel by biodiesel in fuel consumption. Obviously, these biodiesel producers are not allowed to export, diverting production to the domestic market.

6.7.2. Effect of the EU-RED GES threshold

Besides techno-economic factors, the biodiesel export potential depends on the capacity of Argentinean biodiesel producers to fulfil the biodiesel GES threshold imposed by the EU, the main expected destination of Argentinean biodiesel exports. This criterion is currently set at 35% but planned to increase to 50% and 60% in 2017 and 2018, respectively. Therefore, AR biodiesel supply to the EU depends on the satisfaction of this constraint.

Figure 6-10 shows the effect of the biodiesel GES threshold on biodiesel exports for each region. Simulation results show that given regional patterns in soybean land supply, biodiesel producers located in the C region seem to be the only ones that respect the 35% GES threshold imposed in the EU-RED and consequently, they are the only ones allowed to export. Consequently, producers located in the SE, NE, and NO only supply the domestic market.

dLUC GHG emissions seem to be the main issue to be address to improve the overall GHG emission balance of the biodiesel. Table 6-8 show the biodiesel GHG emission balance with and without dLUC emissions. dLUC GHG emissions contribute to 25%, 22%, 33%, 38% and 52% of the GHG emission balance of the biodiesel in each case. Moreover, while no dLUC GHG emissions are relatively similar among supply regions, dLUC GHG emissions large vary across regions.

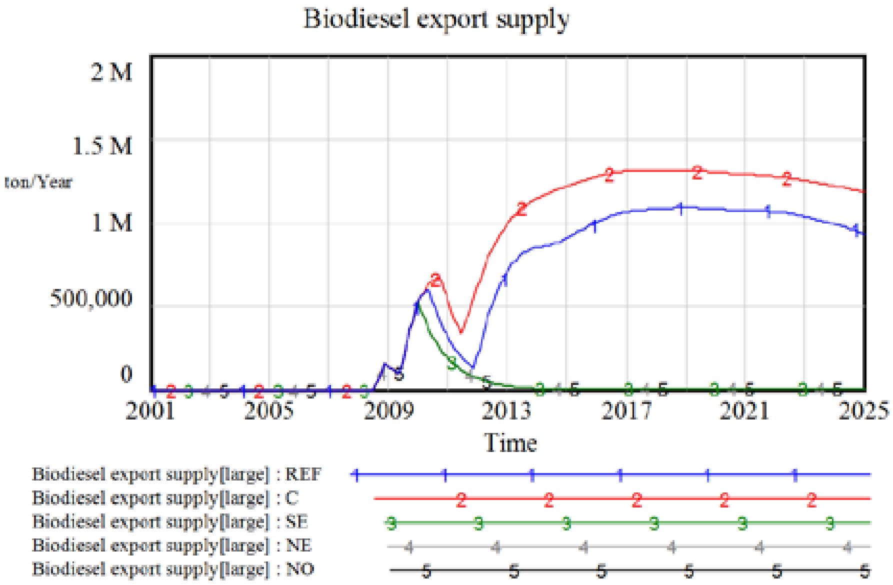

Figure 6-10. Biodiesel export supply by supply region: Effect of the GES threshold.

Table 6-8. GHG emission balance and dLUC threshold for EU-RED GES.

	REF	C	SE	NE	NO
GHG emission balance			gCO2eq/MJ		
No dLUC GHG emissions	38	36	44	42	43
dLUC GHG emissions	13	10	22	26	46
Total GHG emissions	51	46	66	68	89
Fossil reference GHG emissions	83.8	83.8	83.8	83.8	83.8
dLUC GHG threshold			gCO2eq/MJ		
GES-35	16	18	10	12	11
GES-50	4	6	-2	0	-1
GES-60	-4	-2	-10	-8	-9
GES			%		
No dLUC	55%	57%	47%	50%	49%
dLUC	39%	45%	21%	19%	-6%

In the REF case, given the current EU GES threshold of 35%, the GHG emission balance of the biodiesel without dLUC (38 gCO2eq/MJ) and the reference fossil diesel emissions (83.8 gCO2eq/MJ), the margin for dLUC GHG emissions to respect the 35% GES threshold is of 16 gCO2eq/MJ. If current land-use change patterns persist, this value is critical for biodiesel exports, as it is only met by producers located in the C region. In other regions, provided that soybean cultivation emissions are higher, the threshold for dLUC emissions to respect the GES threshold is lower than in the C region. For instance, in the C region the threshold for dLUC GHG is 18 gCO2eq/MJ compared with 10 gCO2eq/MJ in the SE region. This fact constrains the expansion potential of soybean in each region if biodiesel producers are willing to respect the GES threshold.

Additionally, considering the threshold increment to 50% and 60% by 2017 and 2018 respectively, under current land-use patterns the GES threshold will not be fulfilled, even in the C region. For instance, in the C case, when accounting for dLUC GHG emissions the biodiesel GES is 45%. The main consequence is that under current soybean expansion patterns biodiesel exports (from this feedstock) will be constrained in the future. Therefore, on the one hand, this can increase the availability of biodiesel for the domestic market or generate increasing stocks of soybean oil. Provided that soybean meal remains the main driver of soybean production, it is expected that LUC from soybean production will not be significantly affected. This can motivate the development of land-use planning policies or the encouragement of alternative feedstocks that can respect the GES threshold imposed by the EU. These results however are valid at the regional scale.

The scale and the aggregation level seems to play a major role in the estimation of the biodiesel GES. This research shows the variability of GES estimations based on land-use change patterns disaggregated at the regional level. While this allowed estimating the fulfilment of the GES threshold of each soybean supply region, different land-use patterns may be observed at the individual producer level. Indeed, biodiesel producers that are able to demonstrate that they are producing soybeans on current soybean land may use no LUC GHG emissions values. At the local level, this type of assessment can be done, for instance, by using satellite images (Carballo and Hilbert 2010). In a study by Hilbert (2011), for example, an individual biodiesel producer in the NO region is identified. In this study the biodiesel producer states that no land-use changes for soybean production have occurred after January 2008. In this case, the biodiesel producer will be able to export production to the EU market, at least under the 35% GES threshold. Moreover, specific conditions such as the soybean cultivation method, the type of fertiliser used and the transport distances have been defined for the case study. Consequently, the GES of the biodiesel of the biodiesel producer is 73%. In this case, the GES threshold will be fulfilled even for 2017 and 2018.

7. Conclusions

7.1. Synthesis of the PhD thesis

This research aimed to assess the biofuel export potential of a given country accounting for GHG emission reduction constraints imposed in importing countries.

Some countries and regions in the world have set ambitious policies to introduce biofuels in their energy systems. These policies on the one hand, define mainly biofuel blending targets that aim to support biofuel introduction in their domestic markets. On the other hand, they also define sustainability criteria that biofuels should fulfil in order to be traded and supplied to those markets. For several reasons some of these countries are expected to increase their imports of biofuels to achieve their domestic biofuel demand. Consequently, other countries with a potential for biofuel production are seeking to develop their biofuel industry partly to supply the international market.

The ability of producers to export biofuels to those countries/regions is subjected to the fulfilment of the sustainability criteria. One of the critical sustainability criteria is a minimum threshold for the GES of the biofuel. The GES of the biofuel in turn depends mainly on LUC GHG emissions which in certain cases can lead to the non compliance with the GES threshold. This research then, assessed the effect of the key factors including the market structure and evolution, the policy framework and the feedstock production patterns on the export potential of a biofuel producing country.

The thesis focused on the Argentinean case, a major soybean-based biodiesel exporter to the European Union. This case was chosen mainly because of the potential of the country as a biodiesel exporter and the contribution of soybean as a main driver of land-use change in the Argentinean context. Under this scope, the thesis developed a market analysis, a conceptual modeling framework and a system dynamics simulation model to determine the quantity of biodiesel the country may be able to export given the GES threshold imposed in the EU-RED.

The fulfilment of this criterion depends mainly on the contribution of land-use changes, induced by the production of soybean, to the GES of the biodiesel. Therefore, the assessment focused on analysing the biodiesel GES accounting for direct land-use changes at the regional level. To this end, the critical factors that were considered are the structure of the biofuel supply chain, the market dynamics of soybean, value-added and competing products, the domestic policy framework, and the soybean production patterns.

The market analysis assessed the main characteristics of the domestic and international markets for soybean products. Firstly, soybean products were described including the demand drivers, substitutes and production technology and factors. Then the analysis focused on analysing the supply, demand and trade patterns in the international market. To this end, the main market players and the international market structure for soybean products were identified. Additionally, the international price trends for soybean products were analysed based on Agricultural Outlook projections.

In a second step, the market analysis focused on the Argentinean case. Therefore, the soybean-based biodiesel market was described through the analysis of the main market players in Argentina, the domestic policy framework and the link between AR producers and the international market. Finally, the impacts of soybean production in the Argentinean case were discussed through the analysis of historical land-use changes induced by soybean production, the main soybean production patterns and the GHG emission balance of the biodiesel.

The conceptual modeling framework specified the foundations for the assessment of the biodiesel export potential. Firstly, the biodiesel supply chain structure was defined accounting for the main interactions among the soybean producer, the crusher and two types of biodiesel producers. The linkage among producers in the vertical market structure and their linkage to international markets were specified through supply and demand relations. For each producer the intermediate value-added and the international demand functions for each AR product were specified as constant elasticity functions. Additionally, a single input production function was specified for each producer to determine the supply relation for each product in the biodiesel supply chain. Given the specificities of the Argentinean biodiesel policy, biodiesel producers were disaggregated in two types.

In a second step, the modeling foundations for the assessment of land-use changes were specified. The availability of suitable land for agricultural land-uses and the heterogeneity in productivity of cropland and pastures was estimated. A hierarchical structure of land was specified to define an allocation procedure for competing crops and managed lands. Land allocation among competing managed land-uses was modeled based on CET functions depending on the relative unit land profit between competing land-uses. Managed land supply was modeled based on a constant elasticity function depending on the aggregated unit profit of each managed land-use type. Managed land expansion into each unmanaged land-use was modeled based on constant shares in each region estimated through historical patterns.

Finally, the formulation of the GES of the biodiesel was specified based on the GHG life cycle emissions of each unit process involved in soybean-based biodiesel production. For this purpose, the EU-RED methodology was used based on life cycle inventory data for the Argentinean case. A special treatment is given to GHG emissions from soybean cultivation and direct land-use change.

The simulation model implemented the modeling framework in a dynamic simulation environment. Based on system dynamics simulation, the main feedback structures affecting the biodiesel export potential were identified. Two main feedbacks were represented, namely, the effect of the GES threshold and the effect of AR supply on the evolution of international prices of soybean products. Causal loop diagrams and stock and flow diagrams were used to describe the model structure.

The simulation model, implemented in Vensim® for the period 2001-2025, was divided in four main modules to simulate the allocation of biodiesel production among market destinations and producer types, the dynamics of the crushing sector, the competition and supply of land and the GES of the biofuel. External databases were used to introduce a plausible scenario of the evolution of external factors. Structural and behavioural validation tests were then performed to assure the coherence and validity of the simulation model.

The assessment of the biodiesel export potential was performed as follows. Once, the relation among producers in the biodiesel supply chain was specified, a plausible scenario of the market evolution for soybean, value-added and competing products and the domestic policy framework were defined. This scenario, based on the FAPRI 2010 Agricultural Outlook, defined evolution trends for the main factors affecting the market dynamics of each product, including, the international demand trend to be satisfied by AR producers, the price trend of each product in the international market and the technological trend of the product yield in each AR sector.

A reference case was simulated to assess the biodiesel export potential under GHG emission constraints for this scenario and a constant policy framework. Then, the effect of government policies on the biofuel export potential was tested through alternative cases focusing on the domestic biofuel policy and the export tax regime affecting supply of soybean products to the international market.

In a second step, the assessment focused on analysing the effect of land-use change on the biofuel GES at the regional level. To this end, simulations were performed to assess the effect of the feedstock cultivation method and the land-use change patterns in different regions at the sub-national level. Finally, the effect of the EU-RED GES threshold on biofuel exports to the EU was assessed by comparing simulation results of the GES for each region with the threshold imposed by the EU.

7.2. Key findings of the research

The key findings of this research are summarised as follows:

1) Provided that Argentina is the first world exporter of soybean oil, meal and biodiesel, production patterns in Argentina may influence the evolution of international prices of these products. However, despite the large market share of Argentina in the international market for soybean products, the market analysis presented in Chapter 2 seems to indicate that these markets are likely to be competitive. The literature review of previous studies on market power in the soybean complex suggests that Argentina (and other soybean producing countries) seem to behave as price takers.

2) The impact of biodiesel production on soybean land supply was small compared with the effect of other drivers of soybean production. Indeed, land supply for soybean production seems to be mainly influenced by the international demand for soybean meal. In this context, the share of biodiesel on soybean oil demand seems to be still not significant to lead to a possible increment on land supply for soybean production. In the simulation experiments, results show that increasing biodiesel production in Argentina reduce mainly soybean oil exports for the given scenario. However, it may be improbable that farmers will divert more land to produce soybean for biodiesel if soybean land profits are not affected by the biofuel policy. Land supply for soybean production therefore seems to depend more on how Argentinean soybean oil and meal exports affect the price of soybean products in the international market. Moreover, given the joint product relation and the value added attached to soybean meal, the allocation of dLUC to biodiesel production depends mainly on the evolution of soybean oil and meal supply to the international market.

3) Biodiesel domestic policy instruments significantly affect the biodiesel export potential. In the first place, the biodiesel export potential decreases with increasing blending targets. The biodiesel domestic price policy mainly supports biodiesel supply to the domestic market. Removing this policy increases biodiesel exports by 7%, with respect to the REF case. The domestic biodiesel price aligns to the international price that was lower than the simulated

domestic biodiesel price under the *cost-plus* pricing policy. Domestic biodiesel supply quotas support mainly *s&m* firms supplying the domestic biodiesel market. Removing this policy may leave *s&m* firms out of the market and increase biodiesel exports by 18%, provided that large firms are able to produce biodiesel at a lower cost.

4) Export taxes seemed to significantly affect the biodiesel export potential through its effect on producer prices. For instance, increasing the biodiesel export tax by 10% reduced biodiesel exports to zero, provided that biodiesel producers are not able to cover their production costs given the projected evolution of the international biodiesel price. On the other hand, increasing the soybean oil export tax by 10% increases the biodiesel export potential by 24%. In this case, biodiesel production costs are significantly reduced, increasing unit profits for both *s&m* and large firms. Large firms, however, seems to be export oriented, while *s&m* firms are mainly focused on the domestic biodiesel market. Finally, the critical factor affecting soybean land supply was the soybean export tax. For instance, increasing the soybean export tax by 10% reduced soybean land supply by 23%. Consequently, soybean oil and meal supply was also significantly reduced.

5) A main issue in assessing the GES was the soybean supply region. Producers located in the C region seem to be those with the highest potential for exporting biodiesel. FONT farming is the most widespread soybean cultivation method in the region which leads to the lowest GHG emissions in soybean cultivation and the highest soybean yield. Additionally, GHG emissions from dLUC are also the lowest in this region provided that less land is required for soybean production and soybean expands mainly in land with relatively low carbon stocks. Indeed, producers in this region can supply biodiesel to the export market with a GES of 45%. If no dLUC occurs, the GES for biodiesel produced in the C region raise to 57%. On the other hand, producers located in the SE and NE regions supply mainly the domestic market. The high use of CT farming results on higher emissions from soybean cultivation and lower soybean yields. Additionally, cropland expansion into mixedland, grassland, shrubland and forest resulted on significant GHG emissions from dLUC. Producers in these regions can supply biodiesel with a GES of 21% and 18% respectively. Nonetheless, these values do not allow them to fulfil not even the current GES threshold of the EU-RED. Potential for soybean expansion into degraded lands in these regions, however, can increase the GES. Finally, soybean production in the NO will lead to the highest conversion of unmanaged lands, especially forest and the lowest soybean yields. Soybean production in this region therefore, results on the highest GHG emissions from LUC and on a negative GES. Hence, no biodiesel exports are allowed from this region.

6) Finally, particular attention should be given to indirect land-use changes from soybean production. Concentrating soybean production for biodiesel in the C region for instance can displace crops and pastures and may lead to additional land-use changes in other regions. Reducing soybean oil export can also induce displacements in other countries. Additionally, a special treatment should be given to the assessment of iLUC from meal production, accounting for the co-product nature of soybean oil. Indeed, in the Argentinean case simulations showed that soybean oil and meal exports are both expected to increase, independently of biodiesel production. These effects however, can be addressed in a global approach in order to account for trade interactions in international agricultural commodity markets. Short and long term effects can also be distinguished.

7.3. Synthesis of contributions

From a planning perspective, the research contributes to the current knowledge on the assessment of biofuel production impact on land-use change and GHG emissions. The research assessed the effect of GHG emission constraints on the export potential of a biofuel producing countries accounting for GHG emissions from direct land-use change induced by feedstock production for biofuels.

Several countries are investing in the development of their domestic biofuel industries, partially with the aim of diverting part of their production to the international market. In a planning stage, at the producer or governmental level, strategies can be defined to assure that the biofuel is produced in such a way that the GES threshold is respected. Indeed, the assessment of the GES of the biofuel under different policy cases and regional production patterns can provide stakeholders in the biodiesel industry a plausible description of the export opportunities and provide them with science-based inputs to develop biofuel production strategies that respect GHG emission restrictions in importing countries. For instance, concentrating biodiesel production in the C region will lead to the highest export potential and the lowest GHG emissions from land-use change.

The thesis contributes to the understanding of the effect of additional drivers affecting land supply for biofuel feedstock production. In the case of first generation feedstocks, such as soybean, the supply of land for the crop production depends on the derived demand for their value-added products. Additionally, soybean is a multi-product crop, which is mainly produced for meal for feed use and soybean oil for food-use. The higher value attached to soybean meal, given the fixed proportion in output, determined that land supply for soybean production is mainly driven by the meal international price. This relation can change if the value attached to soybean oil increases, for instance, due to a price increment on soybean oil induced by biofuel mandate policies. In this research, given the assumed scenario of demand and prices in the international market for soybean products, biodiesel production did not result in a significant increase in soybean land. Consequently, the allocation of dLUC emissions to biodiesel should account for the contribution of biodiesel production to the overall supply of land for soybean production.

The assessment of the dynamics in the international markets affecting the biofuel supply chain and the definition of a plausible scenario to account for the market evolution helped in the analysis of the additional drivers affecting land supply for soybean production. A critical issue in this assessment was the linkage between the international price of the product and the supply response of the producing country. To this end, a critical analysis was performed of the main players in the domestic and international markets for soybean and value-added products. In this area, the thesis contributed to the analysis of market projections and their implications on the development of the biofuel industry. The thesis discussed the market structure in the domestic and international soybean complex and the price linkage between Argentinean supply of soybean products and their respective demand in the international market. An allocation procedure was then proposed to allocate dLUC emissions to the feedstock production for biofuel use. Assessing the effect of international market dynamics allowed accounting for the complex environment in which the domestic biofuel industry is developed and to account for specific characteristics of joint products and multi-product crops supply.

The conceptual modeling framework contributes to the understanding of actors' interaction in the biofuel supply chain and the influence of external factors on actors' decisions. The thesis explicitly addressed the allocation of biofuel production between the domestic and international markets accounting for the effect of the EU-RED GES threshold. Additionally, the model addressed biofuel allocation among two typologies of biodiesel producers based on the firm size. This detailed assessment allowed accounting for the specific regulations affecting the domestic biodiesel industry. While the modeling framework is specifically developed for the Argentinean soybean-based biodiesel case, some features are common to other biofuel pathways. Indeed, the specification of the biofuel supply chain, the land competition and supply approach and the assessment of the GES of the biofuel can be adapted to model other biofuel pathways, at least in the Argentinean context.

From a system dynamics perspective, the thesis focused on modeling the complex structure of the biofuel supply chain, its market interactions and the land competition between alternative land-uses. The thesis contributed to the identification of the main feedback loops driving producers’ behaviour, especially the price linkage with international markets and the effect of the GHG emissions constraints. Compared with other SD models of biofuels and land-use change, the simulation model explicitly represents biofuel allocation among market destinations and producer types. Moreover, an explicit land-use competition model is included, an issue that was treated in a much more simplified way in previous studies. Furthermore, the LCA model was introduced into the dynamic environment. Previous works have focused on the classical attributional LCA linked to economic models to account for GHG emissions from land-use change.

Finally, the research contributes to the assessment of regional differences on the estimation of the GES of the biofuel. The approach accounts for the regional specificities in feedstock production and the inclusion of direct land-use changes at the sub-national level. Argentinean soybean-based biodiesel presents distinct GES depending on the location of the feedstock. Accounting for these regional differences allowed estimating the biodiesel export potential at the sub-national level by identifying regions that comply (or not) with the EU-RED GES threshold. This data can be used as reference values to be included in current regulations promoting biofuels development, mainly in the EU and the US. Additionally, it can provide valuable information for instance, to plan feedstock production strategies aiming to respect GHG emission reduction constraints or set the basis for detailed assessments at the producer level.

7.4. Main limitations and perspectives for further research

The simulation experiments that were performed are sufficient to illustrate the effect of GHG emission constraints on biofuel exports. The objective was to show how governmental policies, production patterns and exogenous factors can affect the biofuel export potential under the GES threshold. Some simplifications however were necessary to develop the modeling approach. The main limitations of the thesis and the perspectives for further research are summarised as follows:

§ **Policy instruments and external factors:** Simulation experiments were performed assuming a constant policy framework and a single scenario of external factors. Simulation results therefore, are valid in this context. Additional experiments may be develop to assess the biofuel GES and the export potential under other alternative future states.

- **Scale and aggregation issues:** Regional land-use patterns may underestimate the export potential of individual biodiesel producers. The modeling framework may be extended to the individual producer level by identifying and simulating the production strategy of an individual biodiesel producer. A simplified approach was used to simulate international prices and demand for AR soybean products. Indirect land-use changes from soybean production for biodiesel were not included. A more detailed treatment of these issues however will require including complex market interactions in the world economy.
- **Land-use change modeling:** Land-use changes from cropland supply were modeled assuming historical expansion shares into unmanaged lands. This approach does not account for future patterns of land-use change neither for producers’ decisions on the type of unmanaged land-use to be displaced. Moreover, a spatial component may improve the representation of land heterogeneity and the induced land-use changes from soybean production.

Firstly, policy instruments were implemented as constant exogenous variables. This implies that policies were implemented in a given year and maintained until the end of the simulation. Plausible scenarios of the evolution of the policy framework, however, can also be developed and tested. The development of plausible policy scenarios however, requires the involvement of policy makers to define the evolution of policy instruments over time. While several local experts (Table 9-20) were involved in the development of this thesis the research relied mainly on literature and informal consultations. The involvement of policy makers in this process may help in the development of consistent and plausible policy scenarios. Perspectives for further research, so, may include a participatory approach to discuss and validate for instance, scenarios of policy strategies in the medium term.

The same can be said about the evolution of external factors. A single scenario was used assuming projections of the FAPRI 2010 Agricultural Outlook. Alternative scenarios may yield other results with respect to the biodiesel export potential and its effect of land-use change and GHG emissions. Scenario variables can be constructed from any set of consistent projection or assumptions about the market evolution (Blanco Fonseca 2010). Consequently, a perspective for further research is the simulation of the system performance with respect to other scenarios of the evolution of external factors.

This research estimated the biofuel GES at the regional level. While this is appropriate for instance, for their use as default values, they may bias the estimation of the export potential of individual biodiesel producers. Individual biodiesel producers that can certify that the soybeans they use were produced in current soybean field may fulfil the GES threshold of the EU-RED and consequently will be allowed to export. Refining GES of the biofuel at the producer level, however, requires traceability systems that can certify the origin of the feedstock used to produce the biofuel. At present, some current initiatives are developing such types of certification, but their implementation is still on its early stages. An extension of the present research can certainly be the adaptation of the modeling framework at the individual producer level.

The modeling framework focused on the national scale with the system boundaries for the country level. Nonetheless, biodiesel production in Argentina may also impact other countries. That is the case of iLUC where diverting more land for soybean production can generate additional land-use changes abroad. iLUC sources may include the displacement of other crops and pastures and the reduction in soybean oil exports. A proper assessment of iLUC should also account for the co-product nature of soybean oil. These issues can be treated by expanding the model boundaries to include the main interactions with other agricultural producing and consuming regions.

A simplified approach is used to link AR supply to international markets. This type of simplification was necessary to focus on a detailed representation of producers' interaction in the biodiesel supply chain and regional specificities on the estimation of LUC, Therefore, improving this linkage through a global economic approach may improve the simulation of producers' responses in the Argentinean context. This problem can be overcome by adding additional sectors to the model or linking the model to a global economic approach. In practice this means at least defining regions and sectors that represent the main interactions with the representative economic sectors in the country.

The share of each unmanaged land type on cropland expansion was assumed constant and exogenously. While this is a conventional approach, simulations did not account for future patterns of land-use change neither for producers' decisions on the type of unmanaged land-use to be displaced. This limitation can be overcome by further detailing the managed land expansion process. This implies substituting expansion shares by equations that reflect the main variables explaining managed land expansion into each unmanaged land-use type. This process can be extremely complex as land-use change drivers vary significantly depending on local and global socio-economic and environmental conditions.

Finally, the model is not spatially explicit. Spatial representation can help in defining spatial correlation between different land-uses and a more detailed representation of land heterogeneity including carbon stocks in land and feedstock productivity. Linking the modeling framework to a spatial explicit model may overcome these limitations. This implies the identification of the main drivers of feedstock location and further understanding of actors' decisions with respect to spatial patterns of land-use change and feedstock production. Perspectives for further research may include a spatial explicit representation of the model.

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9. Appendix

9.1. Derivation of producers profit maximisation problems.

9.1.1. Soybean producer problem

The aggregated AR soybean producer is modeled as a single profit maximising firm, where total profit of the soybean producer is given by $\pi^{sp}(R_{soy}{}^{sp}, C_{soy}{}^{sp})$. Total profit is defined as total revenue from selling soybean output ($R_{soy}{}^{sp}$) minus total costs from soybean production ($C_{soy}{}^{sp}$). Therefore, the profit maximisation problem of the soybean producer can be written as:

$$\max\left[\pi^{sp} = R_{soy}{}^{sp}(q_{soy}{}^{sp}, P_{soy}{}^{sp}) - C_{soy}{}^{sp}(q_{soy}{}^{sp})\right] \qquad \text{Eq. 9-1}$$

where $q_{soy}{}^{sp}$ is the quantity supplied by the single AR soybean producer and $P_{soy}{}^{sp}$ is the price received by the soybean producer for quantity $q_{soy}{}^{sp}$.

The revenue function of the soybean producer is given by:

$$R_{soy}{}^{sp} = P_{soy}{}^{sp}(q_{soy}{}^{sp}) \cdot q_{soy}{}^{sp} \qquad \text{Eq. 9-2}$$

Production factors accounts for land and non-land inputs, so that the cost function can be expressed as:

$$C_{soy}{}^{sp} = q_{land}{}^{sp}(Y_{soy}{}^{sp}) \cdot P_{land}{}^{sp}(Y_{land,m}{}^{sp}) + \sum_{i} q_i{}^{sp} \cdot P_i^{sp} \qquad \text{Eq. 9-3}$$

where $q_{land}{}^{sp}$ and $P_{land}{}^{sp}$ are quantity and price of land, respectively, that depend on the soybean yield $(Y_{soy}{}^{sp})$, and $q_i{}^{sp}$ and P_i^{sp} are the quantity and price of non-land inputs, where the index *i* denotes the non-land inputs. Assuming all costs are variable costs in the long run (Meyers *et al.* 1991), the total cost for the soybean producer can be expressed as a function of the quantity of soybeans produced, so that,

$$C_{soy}{}^{sp} = \left(Y_{soy}{}^{sp} \cdot P_{land}{}^{sp} + \sum_{i} Y_i{}^{sp} \cdot P_i{}^{sp}\right) \cdot q_{soy}{}^{sp} \qquad \text{Eq. 9-4}$$

The first order condition for the soybean producer indicates that profit maximisation occurs when marginal revenue equals marginal costs. Denoting $MR_{soy}{}^{sp}$ as the marginal revenue of the soybean producer, if the soybean producer behaves as a price taker, then perceived marginal revenue equals price $(MR_{soy}{}^{sp} = P_{soy}{}^{sp})$, giving the profit maximisation solution for a soybean producer selling output in a perfectly competitive market.

Denoting the marginal cost of the soybean producer as $MC_{soy}{}^{sp}$, and assuming non-land input costs are constant, the marginal cost function is given by:

$$MC_{soy}{}^{sp} = Y_{soy}{}^{sp} \cdot P_{land}{}^{sp} \qquad \text{Eq. 9-5}$$

Equalling Eq. 9-5 and Eq. 9-6 so that $MR_{soy}{}^{sp} = MC_{soy}{}^{sp}$, the supply relation for the soybean producer and the derived factor demand functions can be derived. The soybean supply relationship is then given by:

$$P_{soy}{}^{sp} = Y_{soy}{}^{sp} \cdot P_{land}{}^{sp} \qquad \text{Eq. 9-6}$$

9.1.2. Soybean crusher problem

The AR crushing industry is modeled as a single firm that maximises profit. Denoting $\pi^{cr}(R^{cr}, C^{cr})$ the crusher profit from the joint product, the profit maximisation problem is given by:

$$\max \left[\pi^{cr} = \sum_{o} R_o{}^{cr}(q_o{}^{cr}, P_o{}^{cr}) - \sum_{i} C_i{}^{cr}(q_i{}^{cr}, P_i{}^{cr}) \right] \qquad \text{Eq. 9-7}$$

where $R_o{}^{cr}()$ is the total revenue from selling each product *o*. The index *o*, refers to production output, with *o*=meal, oil and $C_i{}^{cr}()$ is the total cost for soybean crushing.

The total revenue function of the soybean crusher is then given by:

$$R^{cr} = (P_{oil}{}^{cr} \cdot Y_{oil}{}^{cr} + P_{meal}{}^{cr} \cdot Y_{meal}{}^{cr}) \cdot q_{soy}{}^{cr} \qquad \text{Eq. 9-8}$$

where $P_{oil}{}^{cr}$ and $P_{meal}{}^{cr}$ are the producer price of soybean oil and meal, and $q_{oil}{}^{cr}$ and $q_{meal}{}^{cr}$ are the quantities produced of soybean oil and meal.

For simplicity, the firm is assumed to use soybean as main input to produce soybean oil and meal in fixed proportions and so, production costs are assumed only to depend on soybean price[43]. The model assumes that the only available input to produce oil and meal is soybean and so the crusher cannot substitute this input by another one. Soybean supply is assumed to be only domestically available meaning that no soybean imports are allowed. Therefore, the cost function of the soybean crusher is given by:

$$C_i{}^{cr} = P_{soy}{}^{cr} \cdot q_{soy}{}^{cr} + C^{cr} \qquad \text{Eq. 9-9}$$

---

[43] Other variable costs are assumed constant.

where $P_{soy}{}^{cr}$ and $q_{soy}{}^{cr}$ is the quantity and price of soybean crushed by the AR soybean oil and meal producer and C^{cr} is a constant accounting for other costs. Soybean crush is assumed to be done by solvent extraction, a mature technology in the crushing industry, and so, conversion yields are assumed constant (Meyers *et al.* 1991).

Denoting the marginal revenue and marginal cost functions for the crusher as MR^{cr} and MC^{cr}, assuming that the aggregated AR firm is a competitive firm with constant returns to scale and deriving $R_o{}^{cr}(q_o{}^{cr}, P_o{}^{cr})$ and $C_i{}^{cr}(q_i{}^{cr}, P_i{}^{cr})$ with respect to the quantity of soybean crushed ($q_{soy}{}^{cr}$), the marginal revenue function can be expressed as :

$$MR^{cr} = \frac{\partial R^{cr}}{\partial q_{soy}{}^{cr}} = P_{oil}{}^{cr} \cdot Y_{oil}{}^{cr} + P_{meal}{}^{cr} \cdot Y_{meal}{}^{cr} \qquad \text{Eq. 9-10}$$

and the marginal cost function can be expressed as

$$MC^{cr} = \frac{\partial C^{cr}}{\partial q_{soy}{}^{cr}} = P_{soy}{}^{sp} \qquad \text{Eq. 9-11}$$

Invoking the first order condition for the soybean crusher, and arranging Eq. 9-10 and Eq. 9-11 so that $MR^{cr} = MC^{cr}$, yields the derived supply relation for soybean crush:

$$P_{oil}{}^{cr} \cdot Y_{oil}{}^{cr} + P_{meal}{}^{cr} \cdot Y_{meal}{}^{cr} = P_{soy}{}^{cr} \qquad \text{Eq. 9-12}$$

9.1.3. Biodiesel producer problem

Biodiesel producers are disaggregated in two types, namely, *s&m* and large firms. Each producer type is modeled as a single firm that maximises profit. Therefore denoting $\pi^{bp}(R_{bio}{}^{bp}, C_{bio}{}^{bp})$ as the biodiesel producer profit, the profit maximisation problem for each biodiesel producer type is given by:

$$\max\left[\pi^{bp} = R_{bio}{}^{bp}(q_{bio}{}^{\exp}, P_{bio}{}^{\exp}, q_{bio}{}^{bl}, P_{bio}{}^{gov}) - C_{bio}{}^{bp}(q_{oil}{}^{bp}, q_i{}^{bp})\right] \qquad \text{Eq. 9-13}$$

The total revenue function for the biodiesel producer is given by:

$$R_{bio}{}^{bp} = q_{bio}{}^{\exp} \cdot P_{bio}{}^{\exp}(q_{bio}{}^{\exp}) + q_{bio}{}^{bl} \cdot P_{bio}{}^{gov} \qquad \text{Eq. 9-14}$$

The total cost function for the biodiesel producer is given by:

$$C_{bio}{}^{bp} = P_{oil}{}^{bp} \cdot (q_{oil}{}^{cr}) \cdot q_{oil}{}^{bp} + \sum_i P_i^{bp} \cdot q_i^{bp} \qquad \text{Eq. 9-15}$$

Denoting $MR_{bio}{}^{bp}$ and $MC_{bio}{}^{bp}$ as the marginal revenue and marginal cost of the biodiesel producer and deriving equations Eq. 9-14 and Eq. 9-15 with respect to $q_{bio}{}^{bp}$, the marginal revenue and marginal cost functions for the each aggregated biodiesel producer is given by:

$$MR_{bio}{}^{bp} = \frac{\partial R_{bio}{}^{bp}}{\partial q_{bio}{}^{bp}} = \beta_{bio}{}^{\exp} \cdot P_{bio}{}^{\exp} + \beta_{bio}{}^{bl} P_{bio}{}^{gov} \qquad \text{Eq. 9-16}$$

$$MC_{bio}{}^{bp} = \frac{\partial C_{bio}{}^{bp}}{\partial q_{bio}{}^{bp}} = P_{oil}{}^{bp} \cdot \Psi_{oil}{}^{bp} \qquad \text{Eq. 9-17}$$

where $\beta_{bio}{}^{\exp}$ and $\beta_{bio}{}^{bl}$ are the share of biodiesel supply to the export and the domestic markets, respectively.

Setting $MR_{bio}{}^{bp} = MC_{bio}{}^{bp}$ so that the biodiesel producer maximises profit and defining the biodiesel producer price as $P_{bio}{}^{bp} = \beta_{bio}{}^{\exp} \cdot P_{bio}{}^{\exp} + \beta_{bio}{}^{bl} \cdot P_{bio}{}^{gov}$ gives the biodiesel supply relation:

$$P_{bio}{}^{bp} = P_{oil}{}^{bp} \cdot (q_{oil}{}^{\exp}) \cdot \Psi_{oil}{}^{bp} \qquad \text{Eq. 9-18}$$

9.2. System dynamics: Theoretical foundation

In this research, system dynamics is proposed as a modeling environment for the implementation of the modeling framework. The key feature of system dynamics simulation models is the identification of closed loop feedback structures, mainly represented as *causal loop diagrams* (CLDs), and implemented in the simulation model as *stock and flow diagrams* (SFD) (Sterman 2000).

Feedback structures, along with stock and flow structures, time delays, and nonlinearities, determine the dynamics of the system (Sterman 2000). Dynamics arise from the interaction of positive (reinforcing) and negative (balancing) feedback loops. Positive loops amplify the change of the system behaviour. On the other hand, negative loops counteract and oppose change. The simulation model, therefore, builds on the identification of positive and negative feedback loops driving the dynamics of soybean-based biodiesel production and export under GHG emission constraints.

Feedback structures are typically represented through CLDs. CLDs are used to get an overview on the causal relationships between the variables of a problem, capturing the dependency between causes and effects (Lane 2008). The usefulness of CLDs relies on their ability to explicitly represent causal relationships. Due to the model complexity, CLDs will be used to describe the main relations between variables and identify the main feedback structures.

CLDs indicate the influences between variables (Figure 9-1). In this representation, reinforcing loops are denotes as R and balancing loops as B. The + sign at the end of the arrow indicates two variables are positively related, and the – sign indicates that variables are negatively related.

An *increase* in **X** results in an *increase* of **Y.** An even number of negative polarities along a loop is a reinforcing loop *R*

An *increase* in **X** results in a *decrease* of **Y** ***An*** odd number of negative polarities along a loop is a balancing loop *B*

Figure 9-1. Causal loops diagrams notation.

These influences must be understood *ceteris paribus*. For instance, if production costs increase, producer profit may decrease. That does not mean it must necessarily decrease, e.g. it will increase if the price increases more than the increase of the production costs. Indeed, the dynamics of the system arises from the interactions among several variables and depends specifically on the functional form of their relation and the value each variable takes over time. Due to inter-relationships between feedback structures and exogenous variables, the behaviour of the whole system cannot be inferred from CLDs representations. This necessitates the need of computer-based simulation models. Consequently, while the CLD gives a preliminary view of how variables are interconnected, simulation is required to determine the behaviour of the system over time. This task implies defining function forms (see Chapter 3) and the variables intensities (values). The resulting system behaviour will depend on the value of exogenous variables estimated through scenarios and the simulated values of endogenous variables that result from the interaction of exogenous variables and feedback structures. Sensitivity analysis can finally be performed to test the influence of parameters and other constant values.

Once the main relation among variables and the main feedback loops are identified, the system dynamics *stock-flow diagram* (SFD) convention is used to represent the structures of the system (Morecroft 1982). In SFDs four types of variables are used, namely: levels (stocks), rates (inflow and outflow), constants (inputs) and auxiliaries (converters) (Figure 9-2).

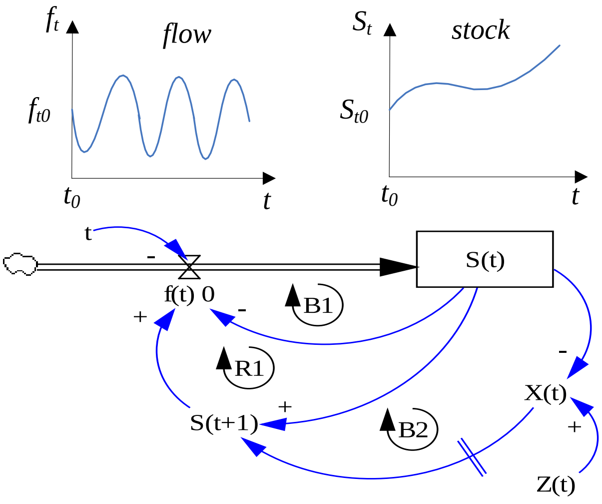

Figure 9-2. Stock-flow diagram convention.

Stocks ($S(t)$) are state variables of the system, indicated by boxes. All feedback loops must contain at least one stock (Fiddaman 1997). The stocks accumulate flows slowly based on their rate, creating the dynamics of the system. Flows ($f(t)$) are represented by pipes. Rates change levels and are symbolised as arrows with a cloud on one end (system boundary). Rates of change are given by derivatives, so that the level of the state variable (stock) is determined by the inflow rate (and the outflow rate). Consequently, while $S(t)$ yields the level of the stock, $f(t)$ indicates the rate of change in the stock level. Constants ($Z(t)$) are assumed fixed values over the simulation period. Auxiliary variables ($X(t)$) are converters or functions that change values immediately, without delay. Auxiliary variables are used to break the flow equations into manageable segments. Delays are used to represent desired states of the stock level ($S(t+1)$).Finally, information links (blue arrows) are used to give input to the auxiliaries and rates.

9.3. Stock and flow diagrams.

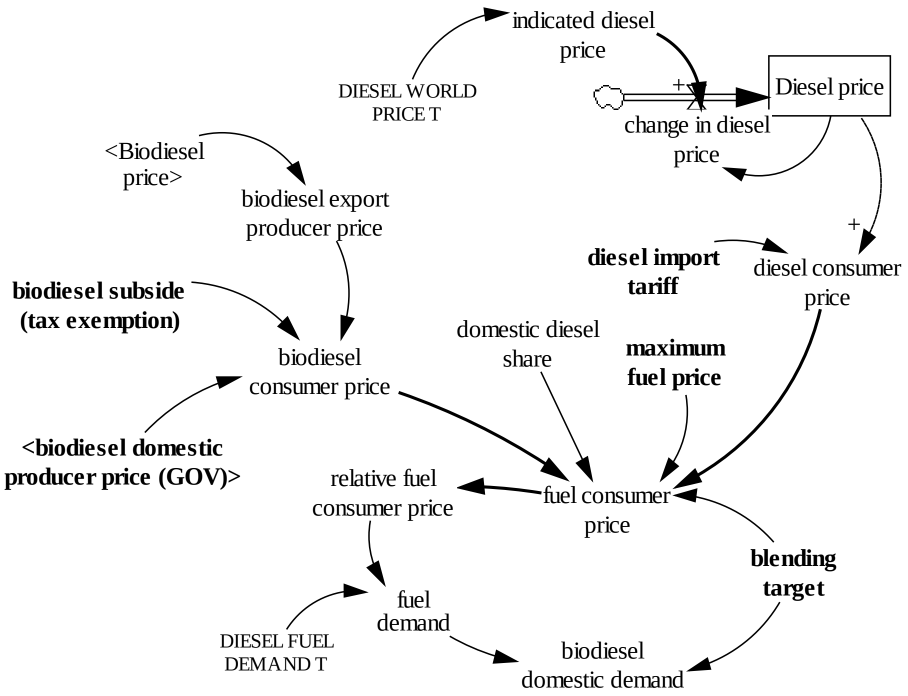

Figure 9-3. Stock and flow diagram: Biodiesel domestic market (BDM) module.

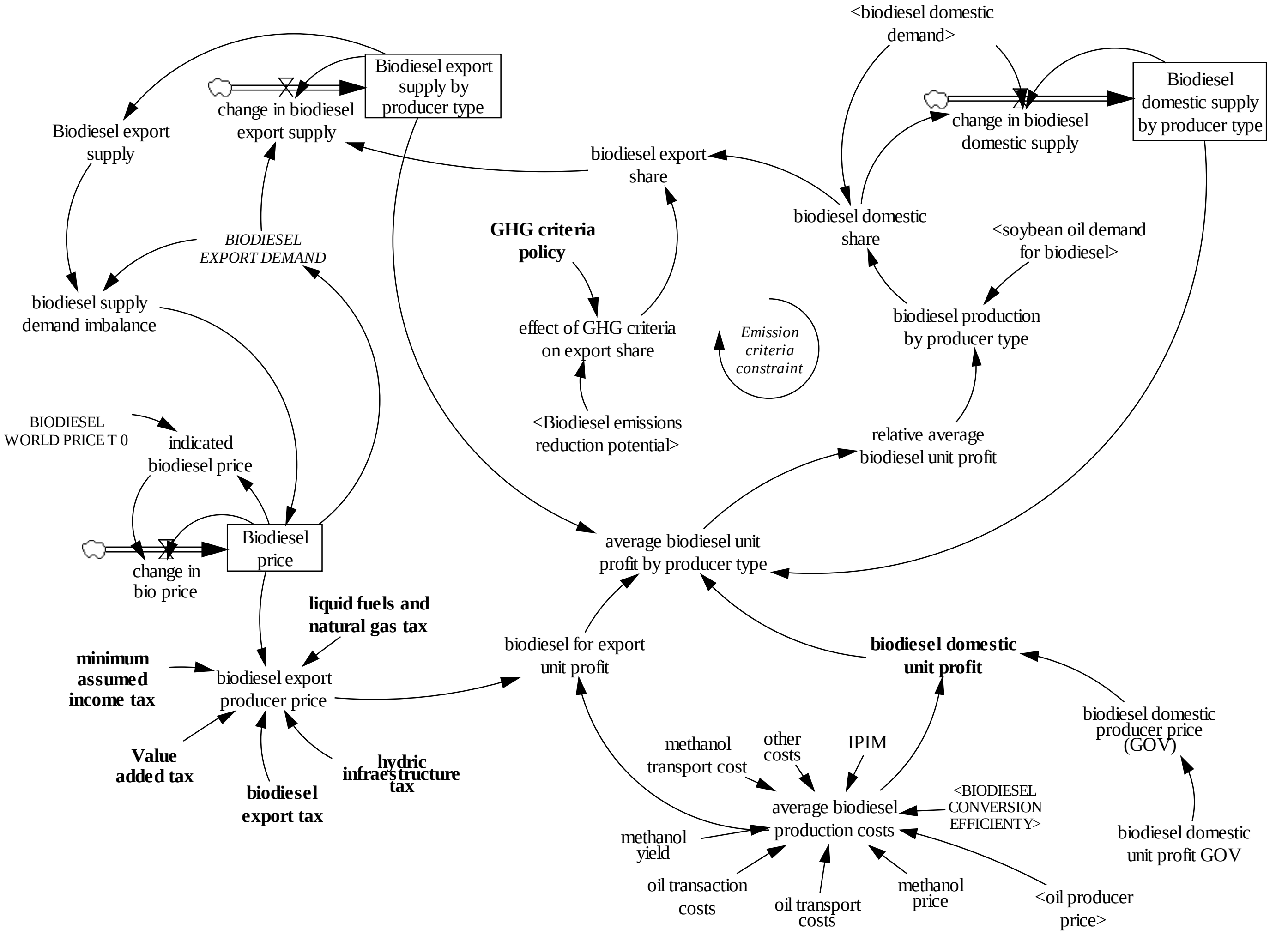

Figure 9-4. Stock and flow diagram: Biodiesel market (BM) module.

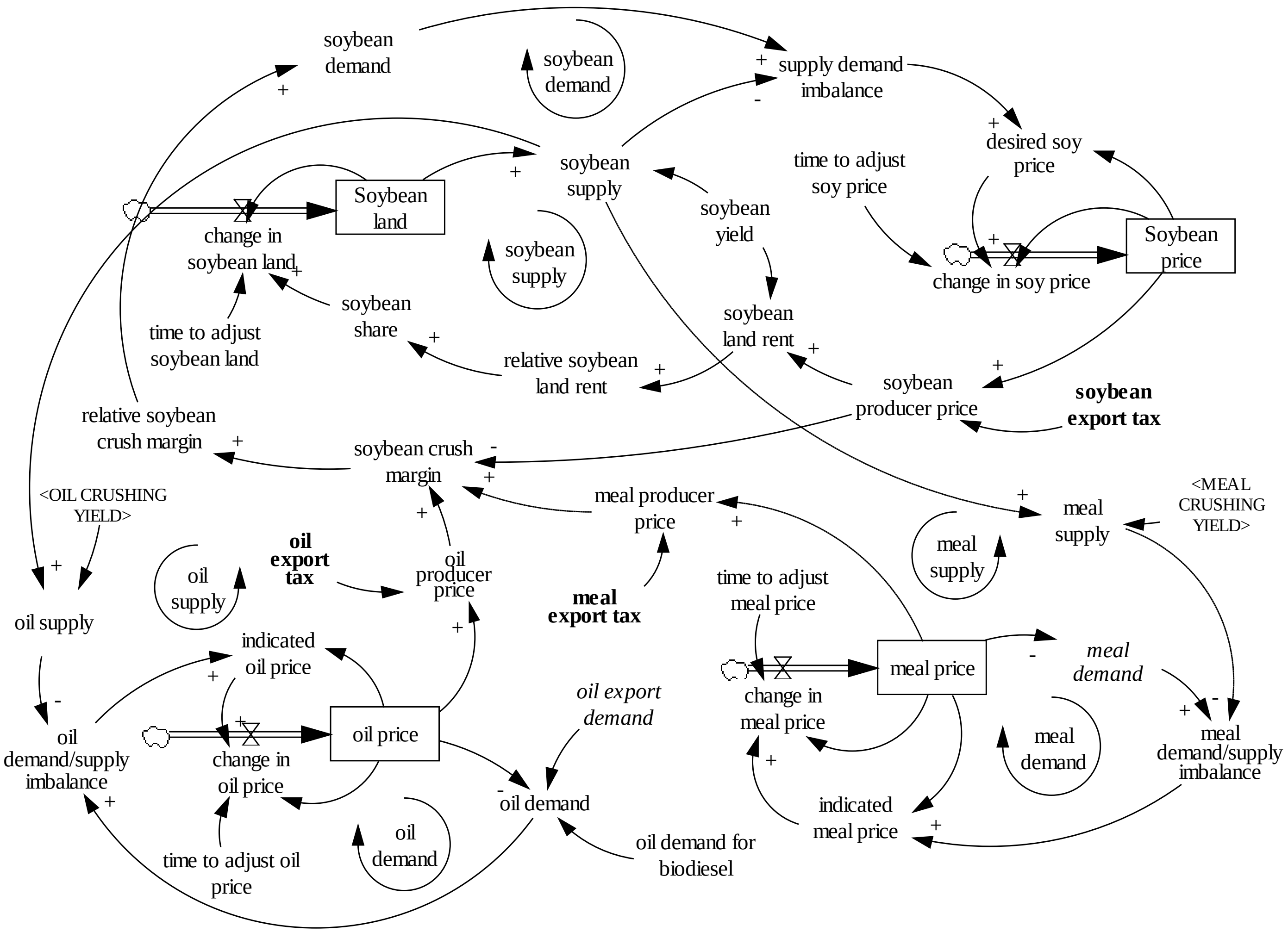

Figure 9-5. Stock and flow diagram: Crushing dynamics (CD) module

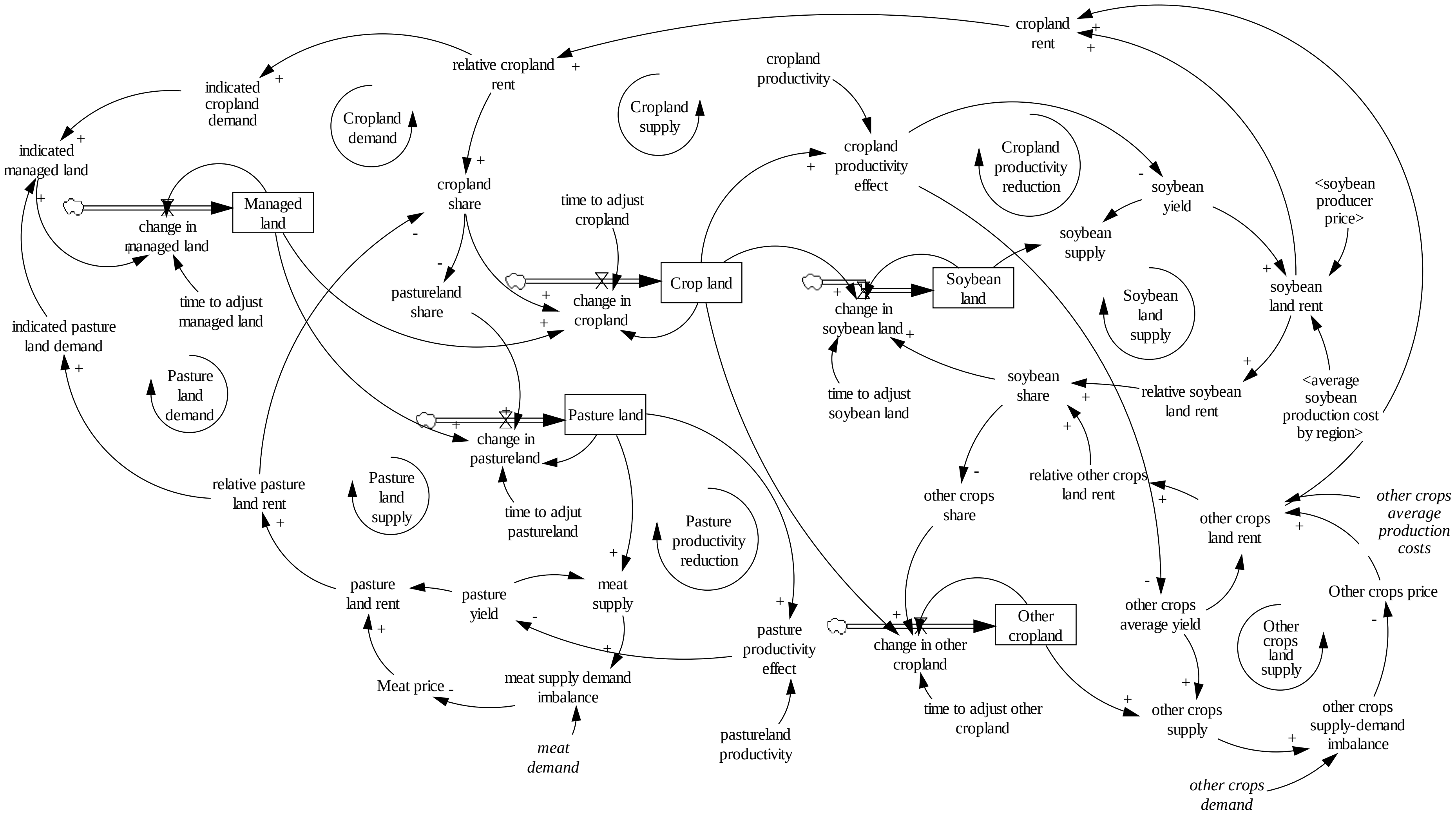

Figure 9-6. Stock and flow diagram: Managed land competition (LCS module).

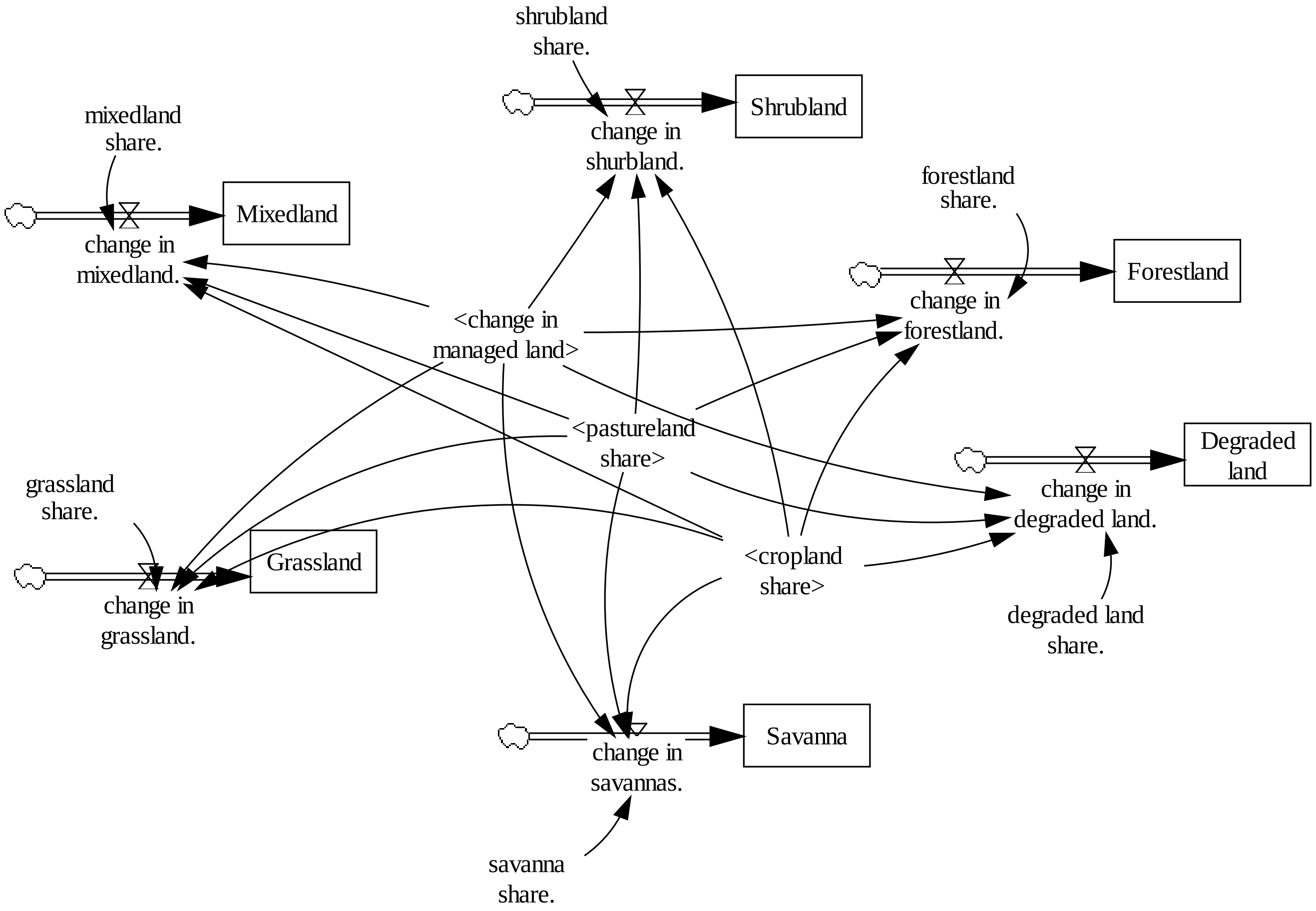

Figure 9-7. Stock and flow diagram: Unmanaged lands reduction (LCS module).

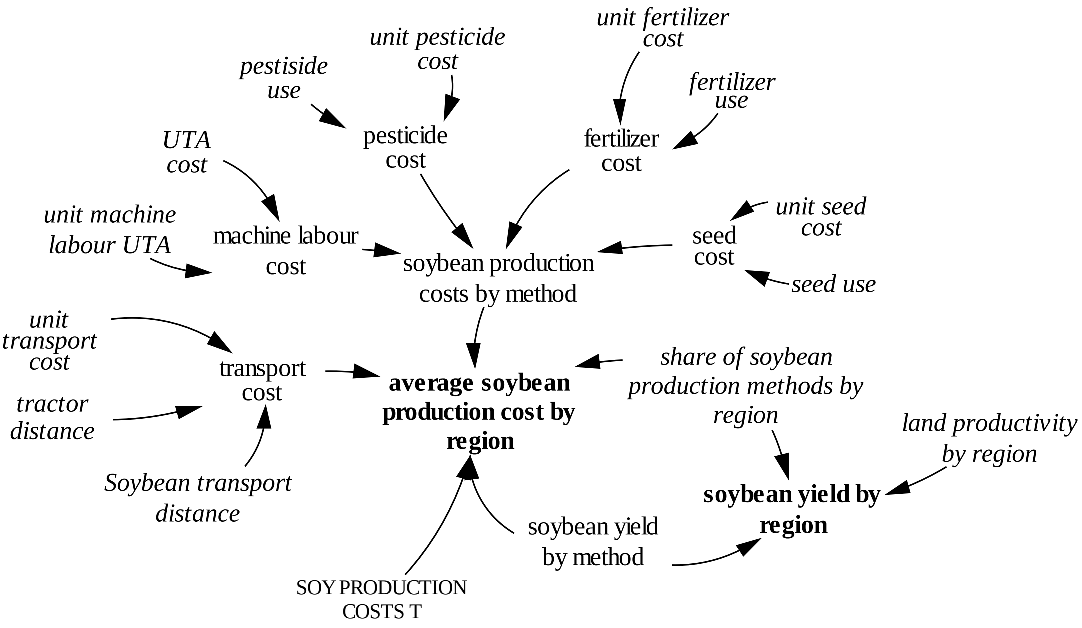

Figure 9-8. Stock and flow diagram: Soybean production methods (SPM) module.

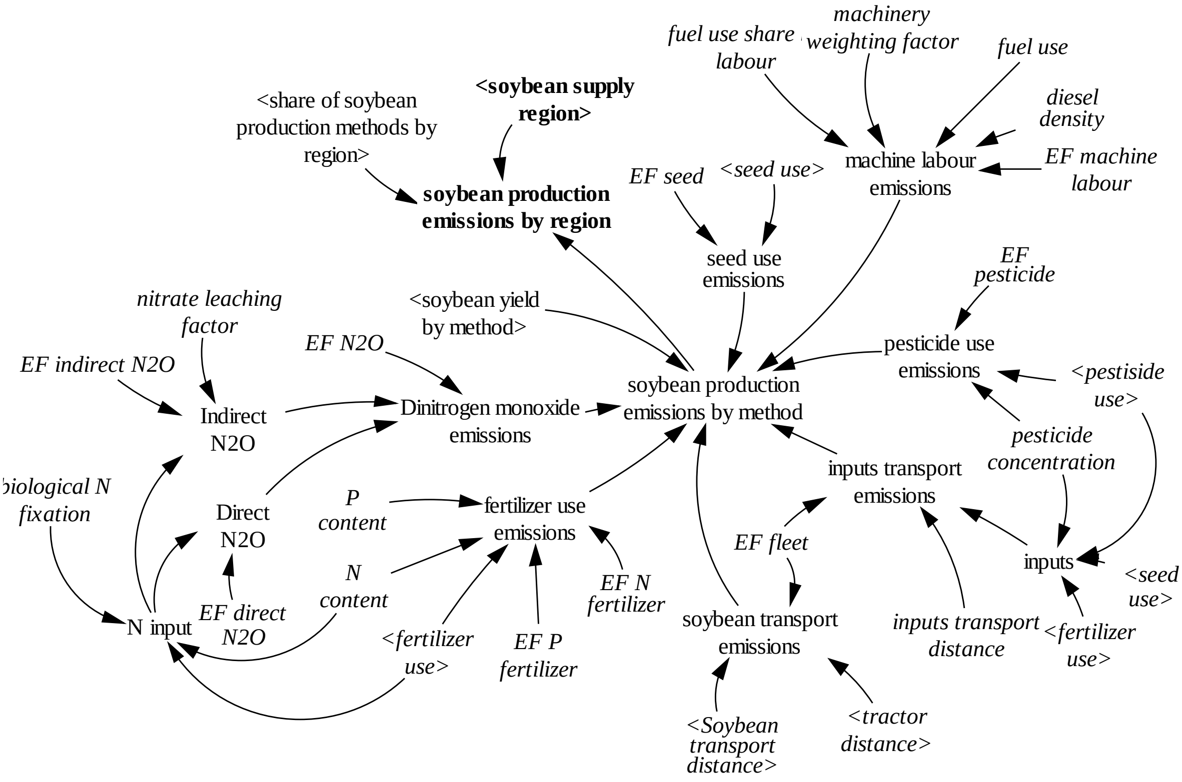

Figure 9-9. Stock and flow diagram: Soybean cultivation GHG emissions (LCA module).

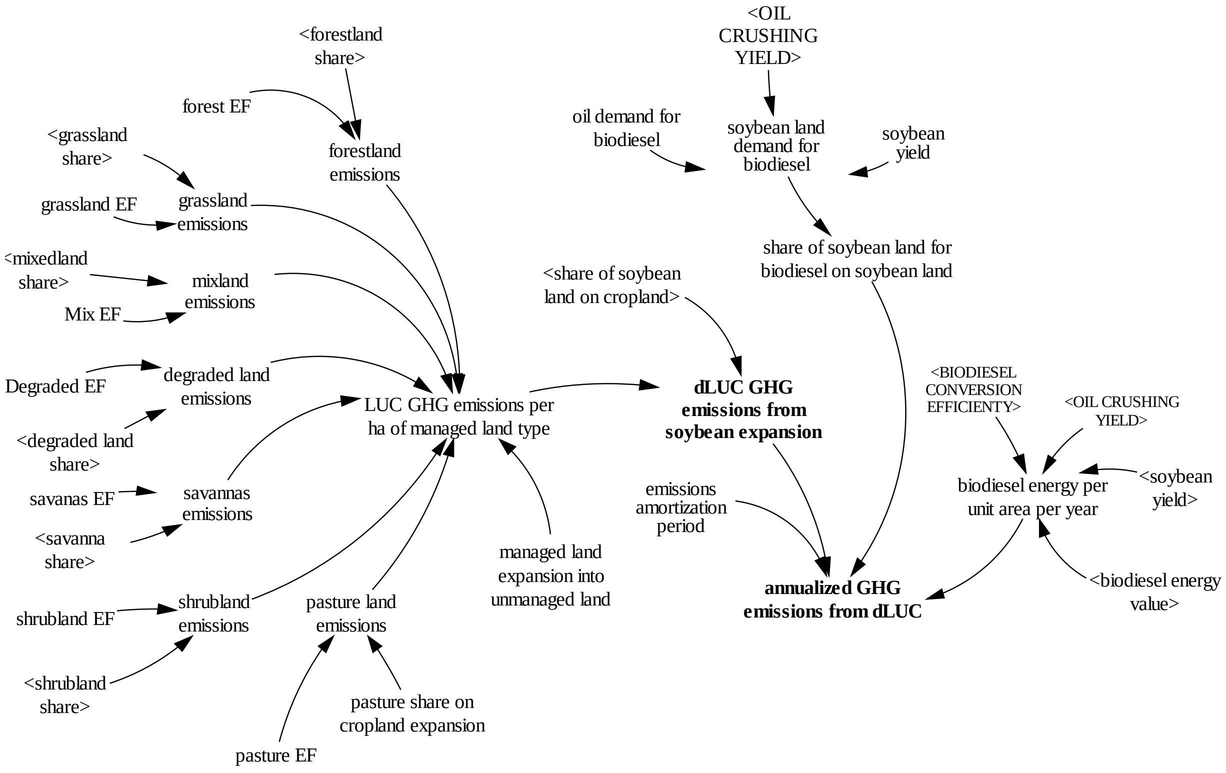

Figure 9-10. Stock and flow diagram: Direct land-use change GHG emissions (LCA module).

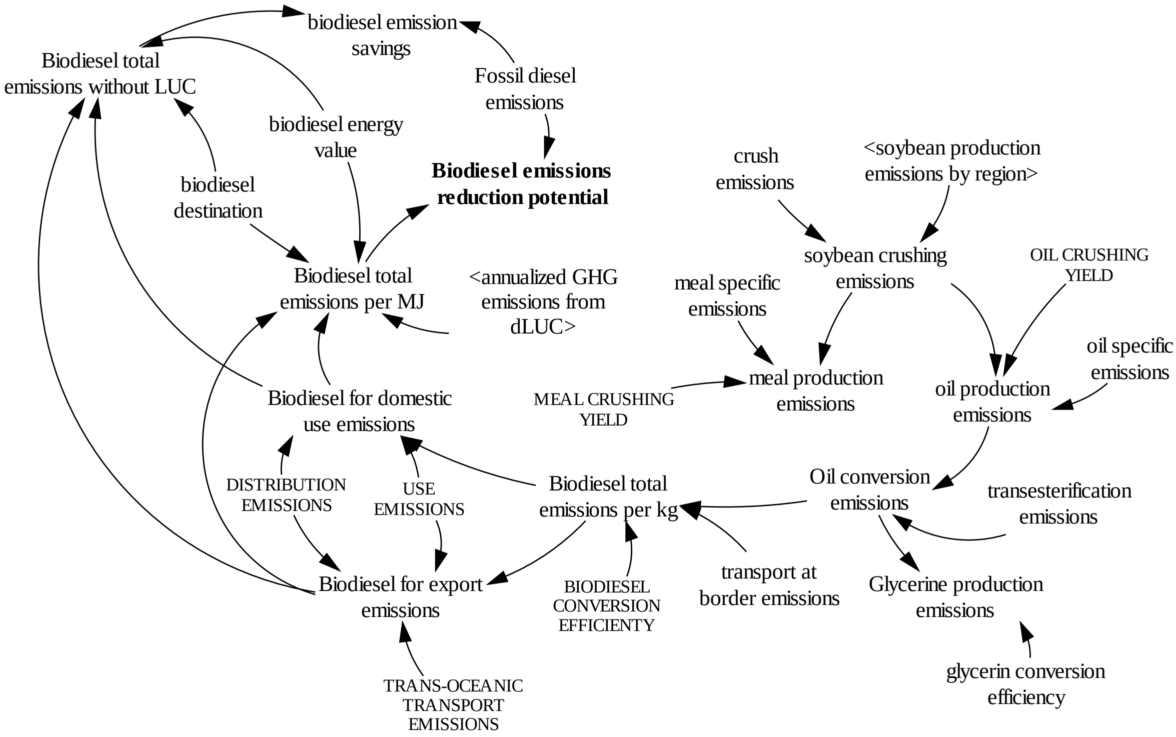

Figure 9-11. Stock and flow diagram: Life cycle GHG emissions and GES (LCA module).

9.4. Input variables and parameters for each module.

Table 9-1. Inputs of the BDM module.

Inputs from database	Symbol	Value	Units	Source
Biodiesel blending target	a_{bio}^{gov}	7	%	PF
Fuel price cap (maximum fuel price)	P_{fuel}^{gov}	1	dmnl	PF
Diesel import tariff	w_{diesel}	20	%	PF
Biodiesel domestic unit profit	g_{bio}^{bp-gov}	28	US$/ton	PF
Biodiesel additional taxes	x_{bio}	Table 9-2	%	PF
Fuel (domestic) demand trend	d_{fuel}^{c}	1.8	%	AO
Diesel price	P_{diesel}^{imp}	Table 6-3		AO
Variables from other modules				
Biodiesel domestic producer price	P_{bio}^{gov}		US$/ton	BM
Biodiesel export producer price	$P_{bio}^{\exp}$		US$/ton	BM
Parameters				
Time to adjust diesel price	t_{dp}	0.833	Year	BDM
Fuel demand elasticity	e_{fuel}	-0.2	dmnl	BDM

Table 9-2. Biodiesel additional taxes by market destination.

Biodiesel additional taxes	Value		Units	Note
	Export	Domestic		
Liquid fuel and natural gas tax	0.05	0	%	Biofuel law
Minimum assumed income tax	1	0	US$/ton	Biofuel law
Value-added tax	2.5	0	%	Biofuel law
Hydro infrastructure tax	1.5	0	%	Biofuel law

Table 9-3. Inputs of the BM module.

Inputs from database	Symbol	Value	Units	Source
GHG threshold	er_b^{imp}	35	%	PF
Biodiesel domestic supply quota by firm type	a_{bio}^{f}	80,20	%	PF
Biodiesel domestic unit profit	g_{bio}^{bp-gov}	28	US$/ton	PF
Biodiesel international price trend	c_{bio}	4.1	%	AO
Biodiesel export tax	w_{bio}	17.5	%	PF
Biodiesel additional taxes	x_{bio}	Table 9-2	%	PF
Other production costs	C_{bio}^{is}	Table 9-4	US$/ton	AO
AR Biodiesel international demand trend	$d_{bio}^{\exp}$	1.9	%	AO
Biodiesel conversion yield	Y_{bio}^{bp}	0.9	ton/ton	AO
Variables from other modules				
Soybean oil price to the biodiesel producer	P_{oil}^{bp}		US$/ton	CD
GHG emission saving	$er_{bio,sr}$		%	LCA
Biodiesel domestic demand	q_{bio}^{bl}		ton/year	BDM
Parameters				
Biodiesel supply elasticity [s&m, large]	e_f	0.2, 0.3	dmnl*	BM
Biodiesel demand elasticity	e_{bio}^{c}	-0.32	dmnl	BM
Time to adjust biodiesel supply [s&m, large]	t_f	0.5, 0.3	Year	BM

Table 9-4. Biodiesel non-feedstock cost data by producer type.

Parameter	Value		Units	Note
	s&m	*Large*		
IPIM	0.98	0.98	Dmnl	Biodiesel law
Methanol yield	0.155	0.155	ton/ton	Biodiesel law
Methanol price	700	500	US$/ton	Biodiesel law
Oil/methanol transport costs	10	5	US$/ton/km	Biodiesel law
Oil transaction costs	5	0	%	Biodiesel law
Other costs	163.75	200	US$/ton	Biodiesel law

Table 9-5. Inputs of the CD module.

Inputs from database	**Symbol**	**Value**	**Units**	**Source**
Soybean export tax	w_{soy}	0.35	%	PF
Soybean oil export tax	w_{oil}	0.32	%	PF
Soybean meal export tax	w_{meal}	0.32	%	PF
AR soybean international demand trend	$d_{soy}^{\exp}$	2.3	%	AO
AR soybean oil international demand trend	$d_{oil}^{\exp}$	6.4	%	AO
AR soybean meal international demand trend	$d_{meal}^{\exp}$	4.9	%	AO
Soybean international price trend	$d_{oil}^{\exp}$	1	%	AO
Soybean oil international price trend	$d_{oil}^{\exp}$	3.9	%	AO
Soybean meal international price trend	$d_{oil}^{\exp}$	-1.1	%	AO
Soybean oil conversion yield	Y_{oil}^{cr}	0.2	ton/ton	AO
Soybean meal conversion yield	Y_{meal}^{cr}	0.8	ton/ton	AO
Inputs from other modules				
Soybean yield	Y_{soy}^{sp}		ton/ha	SPM
Soybean land supply	q_{land}^{sp}		ha/year	LCS
Soybean land unit profit	g_{land}^{sp}		US$/ha	LCS
Soybean production costs	C_{soy}^{sp}		US$/ha	SPM
Competing land unit profit	g_{land}^{cc}		US$/ha	LCS
Parameters				
Crush margin elasticity	e_{cr}	0.2	dmnl[*]	BM
Soybean international demand elasticity	e_{soy}^{c}	-0.2	dmnl	BM
Soybean oil international demand elasticity	e_{oil}^{c}	-0.35	dmnl	BM
Soybean meal international demand elasticity	e_{meal}^{c}	-0.35	dmnl	BM
Time to adjust soybean, oil, meal price	t_o	0.0833	Year	BM

[*] dmnl: dimensionless

Table 9-6. . Input of the LCS module.

Inputs from database	Symbol	Value	Units	Source
Share of unmanaged land k on managed land l supply	$a_{l,k}^{sr}$	Table 9-7	%	LUC
Share of soybean cultivation methods	$a_{sr,m}^{sp}$	Table 9-8	%	SPM
Land productivity	p_{sr}	Figure 9-12	dmnl*	GIS
Beef price	P_{l2}^{c}	Table 6-3	%	AO
Cattle production costs	C_{l2}^{c}	Table 9-10	US$/ha	CIC
Beef export tax	w_{l2}	0	%	AO
Pasture land yield trend	Y_{l2}^{cc}	1.2	%	AO
Competing crop production cost	C_{n2}^{cc}	Table 9-10	US$/ha	CIC
Competing crop export tax	w_{n2}	20	%	AO
Competing crop international price	$P_{n2}^{\exp}$	Table 6-3	US$/ton	AO
Competing crop yield trend	Y_{n2}^{cc}	0	%	AO
Suitable available agricultural land	Q_{land}^{T}	Table 9-9	ha	GIS
Inputs from other modules				
Soybean international price	$P_{soy}^{\exp}$		ton/ha	CD
Soybean production costs	C_{soy}^{sp}		US$/ha	SPM
Soybean yield by method	$Y_{sr,m}^{sp}$		ton/ha	SPM
Parameters				
Crops elasticity of transformation	s_n	0.5	dmnl	LCS
Managed land elasticity of transformation	s_l	0.3	dmnl	LCS
Managed land supply elasticity [cropland, pasture]	e_l	0.2, 0.4	dmnl	LCS

* dmnl: dimensionless

Table 9-7. Land-use change patterns by region.

Region	SE	NE	NO	C
Cropland		%		
Forest	0.001	0.036	0.159	0.035
Grassland	0.148	0.439	0.331	0.487
Mixed	0.569	0.421	0.266	0.323
Savannas	0.193	0.092	0.230	0.127
Shrubland	0.066	0.001	0.009	0.020
Wetland	0.024	0.010	0.004	0.009
Pasture				
Forest	0.002	0.117	0.250	0.129
Grassland	0.202	0.424	0.256	0.371
Mixed	0.207	0.236	0.138	0.135
Savannas	0.260	0.173	0.299	0.244
Shrubland	0.277	0.007	0.051	0.094
Wetland	0.052	0.042	0.006	0.026

Table 9-8. Production methods initial shares and fuel use.

Methods	Initial shares by region				Fuel use
	%				lt/ha
	C	**SE**	**NE**	**NO**	
FONT (First occupation no-tillage)	80	20	50	50	27.72
SONT (Second occupation no-tillage)	20	30	0	50	22.92
FOCT (Second occupation conventional tillage)	0	50	50	0	51.52

Table 9-9. Initial land stocks.

Land-use type	Area	Percentage share
	ha	%
Other crops	2450000	51
Soybeans	11400000	49
Cropland	23397000	40
Pastureland	35020757	60
Managed lands	58417757	100
Forest	30229973	14
Grassland	29873811	14
Mixed	14781847	7
Savannas	21213987	10
Shrubland	116129913	54
Degraded	3290975	2
Unmanaged lands	215520506	100
Suitable available agricultural land	273938263	100

Table 9-10. Initial costs and costs annual increments.

Production costs	Initial cost (2001)	Cost annual increment
	US$/ha	US$/ha
Corn	565	5
Meat	834	60
Soybean FONT	427	-
Soybean SONT	302	-
Soybean FOCT	451	-

Table 9-11. Own price elasticity of area supply for competing crops and pasture in Argentina.

Land-use type	Value	Note
Soybeans	0.32	Area elasticity, FAPRI
Corn	0.70	Area elasticity, FAPRI
Pasture	0.11	Short-run breeding stock elasticity for cattle and calves

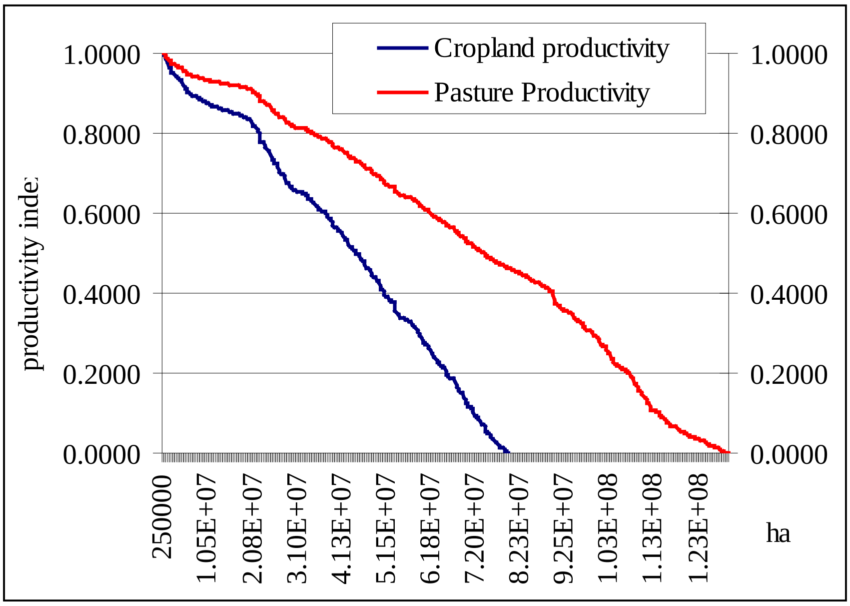

Figure 9-12. Cropland and pasture productivity.

Table 9-12. Input of the LCA module.

Inputs from database	**Symbol**	**Value**	**Source**
Soybean inputs emission factors	ef_i	Table 9-13 Table 9-17	LCI
Soybean input quantities by cultivation method	$q_{i,m}^{sp}$	Table 9-13 - Table 9-17	SPM
Share of soybean cultivation methods	$a_{soy,sr}^{sp}$	Table 9-8	SPM
LUC emission factors	ef_k , ef_l	Table 9-18	LCI
Reference fossil fuel emissions	e_f	Table 9-19	LCI
Industrial, transport, distribution and use emissions	ep, etd, eu	Table 9-19	LCI
Energy content of each product	mj	Table 9-19	LCI
Conversion yields	Y_o^p	Table 9-19	AO
Inputs from other modules			
Producer prices	P_o^p		CM, BM
Unmanaged land *k* reduction from cropland *l* expansion	$q_{l,k}$		LCS
Pasture land reduction from cropland expansion	$q_{l,l}$		LCS
Soybean share in cropland expansion	a_{soy}^{l}		LCS
Soybean for biodiesel share on soybean expansion	a_{soy}^{bio}		LCS
Average soybean land yield	Y_{soy}^{sp}		LCS

* Functional unit of each soybean production input.

Table 9-13. Fertiliser inputs, costs and emission factors.

Fertilisers	**Use**			**Cost**	**NP content**		**Emission factors**	
	FONT	SONT	FOCT		N	P	P EF	N EF
	kg/ha	kg/ha	kg/ha	US$/kg	%	%	kgCO2eq/kg	kgCO2eq/kg
monoammonium phosphate	0	0	0	0.38	0.12	0.52	1.655	2.927
triple superphosphate	80	0	75	0.48	0	0.46	2.076	0

Table 9-14. Pesticide inputs, costs and emission factors.

Pesticide	**Use**			**Cost**	**Concentration**	**Emission factor**
	FONT	SONT	FOCT			
	kg/ha	kg/ha	kg/ha	US$/kg	%	kgCO2eq/kg
2-4D	0	0	0	4.5	100	3.232
glyphosate	8	6	5	2.65	58	15.938
cypermethrin	0.12	0.12	0.12	12	17	19.995
clorpyriphos	1.2	0.5	1.2	7.92	48	7.73
deltamethrin	0	0	0	15	25	19.995
endosulfan	0.3	0.23	0.3	69.66	35	6.091
metsulfuron	0.005	0	0	36	60	9.203

Table 9-15. Machine labour parameters.

Machine labour	UTA use[*]			Fuel use share by labour			Weight	Emission factor
	FONT	SONT	FOCT	FONT	SONT	FOCT	WF	EF
	units	units	units	%	%	%	dmnl	kgCO2eq/ha
ploughing	0	0	1.3	0%	0%	48%	26	118.48
chiselling	0	0	1	0%	0%	14%	15.52	71.309
harrowing	0	0	0	0%	0%	4%	4.44	24.701
sowing	1.1	1.1	0.7	12%	14%	4%	3.82	22.643
currying by weeder	0	0	0	0%	0%	0%	1.6	10.881
plant protection	1.58	1.05	1.23	33%	20%	5%	1.76	10.949
fertilisation	0.35	0.35	0.35	17%	20%	5%	5.29	25.183
harvesting	2.5	2.5	2.5	38%	46%	21%	33.31	154.77

UTA cost	24	US$/ha
Diesel density	0.84	kg/lt

[*] Agricultural labour is measures as UTA (Agricultural Labour Units). Fuel use by method is distributed within agricultural labours to estimate GHG emissions.

Table 9-16. Seeds use and emission factors.

Seed	Seed use	EF
	kg/ha	kgCO2eq/kg
Soybean	8.00E+01	1.151

Table 9-17. Transport distances and costs.

Transport distances	Region	Initial distance	Cost	Emission factor
		ton.km	US$/ton.km	kgCO2eq/ton.km
Tractor and trailer		30	0.21	0.307
Lorry 28t	C	200	0.08	0.193
	SE	400	0.08	0.193
	NE	600	0.08	0.193
	NO	1000	0.08	0.193

Table 9-18. Land-use emissions factors (20 years).

Cropland to	tonCO2eq/ha	Pasture to	tonCO2eq/ha
Forest	198.64	Forest	153.30
Grassland	77.14	Grassland	0.00
Savannas	44.56	Savannas	0.00
Shrubland	94.30	Shrubland	25.73
Mixed	86.47	Mixed	23.27
Degraded	-55.61	Degraded	-55.61
Pasture	63.61	Cropland	52.81

Table 9-19. Parameters for complete LCA emission balance estimation.

Parameters	**Value**	**Units**
Unit process emissions		
Crushing	0.061	kgCO2eq/kg soybean
Transesterification	0.402	kgCO2eq/kg oil
Transoceanic transport and distribution	0.068	kgCO2eq/kg biodiesel
Domestic transport and distribution	0.033	kgCO2eq/kg biodiesel
Use emissions	0	kgCO2eq/kg biodiesel
Energy content		
Oil	37.2	MJ/kg
Meal	17	MJ/kg
Biodiesel	37.2	MJ/kg
Glycerine	18	MJ/kg
Conversion yields		
Oil	0.2	ton/ton
Meal	0.8	ton/ton
Biodiesel	0.9	ton/ton
Glycerine	0.1	ton/ton
Glycerine price	100	US$/ton
Fossil diesel emissions	83.8	gCO2eq/MJ

9.5. Market evolution assumption

9.5.1. Soybean, corn and beef market assumptions

In the soybean international market, Argentina is mainly a small country, accounting for an average market share of 14%. Argentinean share of soybean exports remain constant over the projection period. Soybean exports are projected to increase due to a projected increase in the processing capacity of the crushing industry in China. The soybean international price remains almost constant at 429 US$/ton with a slightly upward trend over the simulation period. Soybean yield increases from 2.9 to 3.2 ton/ha given the assumed technological improvements.

Argentina is the second world exporter of corn with a 18% market share on corn exports in 2011. Argentinean corn exports are expected to increase in the next years mainly due to reduced export supply by the US in order to fulfil their ethanol blending mandate. However, the Argentinean corn export market share is expected to decrease to 9% mainly because corn exports supply by the US are expected to increase, given the increased production of cellulosic ethanol. Corn yields have significantly increased in past years from 5.45 to 8.33 ton/ha from 2001 to 2010. However, projections indicate that corn yield will remain constant in the next years. Corn domestic demand on the other hand is projected to increase due to increased meat demand (and consequently corn as animal feedstock) and the projected increase in income of Argentinean consumers.

In the beef international market, Argentinean share on meat exports is small; given that 92% of the Argentinean beefs production is supplied to the domestic market. Meat production therefore depends mainly on domestic meat price. Projections indicate an increment in both meat domestic use and exports. However, market destination shares are kept in the same proportions.

9.5.2. Soybean oil and meal market assumptions

Soybean co-products account mainly for soybean oil and meal. Argentina currently exports 99% and 92% of its soybean oil and meal production. Domestic demand for food is low due to Argentinean consumers’ preference for sunflower oil and the availability of pastureland for livestock production. Soybean demand for crush accounts for 85% of Argentinean soybean demand. Consequently, the excess soybean international demand is assumed a scenario variable.

Argentinean share of soybean oil and meal in the international market is projected to increase for both products; from 56% to 73% for soybean oil and from 47% to 62% for soybean meal, respectively by 2025. Projections indicate that these increments are mainly due to reduced exports supply by Brazil and US to supply their respective domestic markets.Despite the important market share of Argentina in oil and meal exports these commodity markets are quite well structured and competition conditions seem to prevail.

9.5.3. Diesel and biodiesel market assumptions

Argentinean currently dominates half of the biodiesel export market, being the first world exporter of biodiesel. Biodiesel exports however are projected to decrease from 56% to 41% by 2025. This is mainly due to increased biodiesel demand in the domestic market but also because of a reduction in biodiesel exports by other countries and the increased production capacity in biodiesel importing countries.

The domestic supply of biodiesel is regulated by the government (not accounted for in the FAPRI baseline). The FAPRI baseline assumes a B5 blending target that generates a domestic biodiesel demand of 559 kton/year in 2010 with a slight increment to 664 kton/year by 2025 given by the increased fuel consumption.

In the diesel international market, Argentinean share on diesel imports is significantly small, so, Argentina is assumed not to affect the price of imported diesel. Crude oil price is projected to increase over the outlook from 59.4 in 2010 to 94.2 US$/barrel in 2020. The increment in crude oil price sustain diesel price following a similar pattern. On the other hand, diesel fuel consumption is projected to increase by 1.96 Mtons from 2010 to 2020, at an annual rate of 205 kton/year. After recovery, annual economic growth in Argentina is projected to average 3.6% increasing fuel consumption, despite a significant increment in price inflation.

9.6. Pastureland expansion patterns by supply region

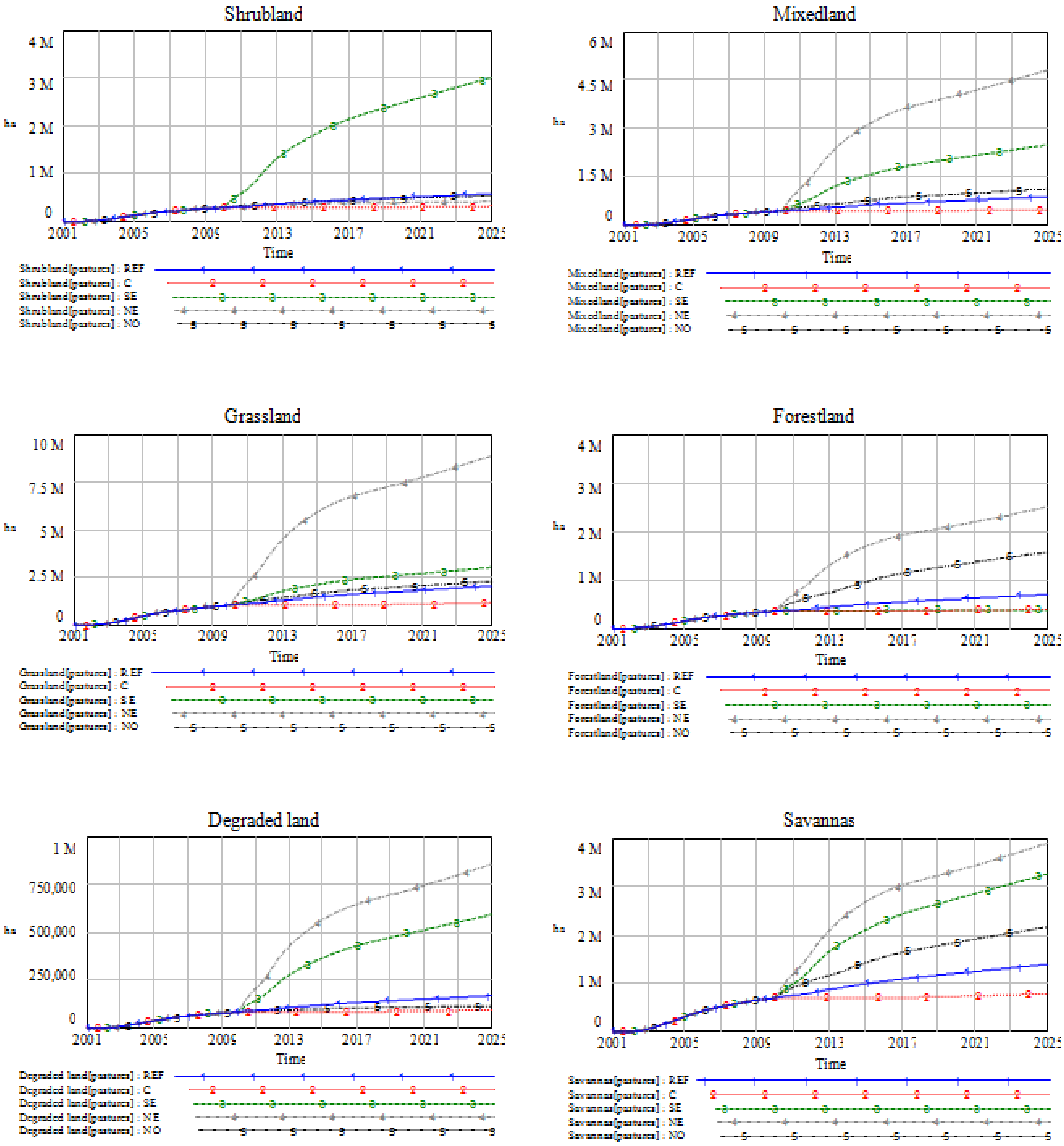

Figure 9-13. Pastureland expansion patterns by supply region.

9.7. Sensitivity analysis of elasticity values

Sensitivity analysis is performed with respect to two key elasticity parameters affecting the biodiesel export potential under GHG emission restrictions, namely unit profit elasticities and land transformation elasticities.

Elasticity values are difficult to obtain and can largely vary according to the type of historical data used and the method used to obtain them. Moreover, the aggregation level also plays a major role. For instance, Barr *et al.* (2010) estimated land supply elasticities for Brazil and the United States. They found that elasticity values largely vary depending on the land types and regional aggregation level. Moreover, they use net return elasticities that account for variability in cost, in contrast to the formal approach of using price data. For this research elasticity values where obtained from literature when available and others were calibrated to feet model requirements. The elasticity values used in the model may have a significant impact on model results (Edwards *et al.* 2010b). Consequently, alternative elasticity values should be tested to assess their effect on the biodiesel export potential.

To this end, a multivariate sensitivity simulation (MVSS) is performed with random uniform probability distribution functions. Random uniform is the simplest distribution, in which any number between the minimum and maximum values is equally likely to occur. This functional form was assumed because of lack of data on alternative elasticity values. Moreover, maximum and minimum values were arbitrary set on the range ± 0.5 for each elasticity value.

Figure 9-14 shows the MVSS for unit profit elasticities in the simulation model. Simulations show that the biodiesel export potential can vary in the rage of 0- 2 Mtons/year as a result of the variability in unit profit elasticity values.

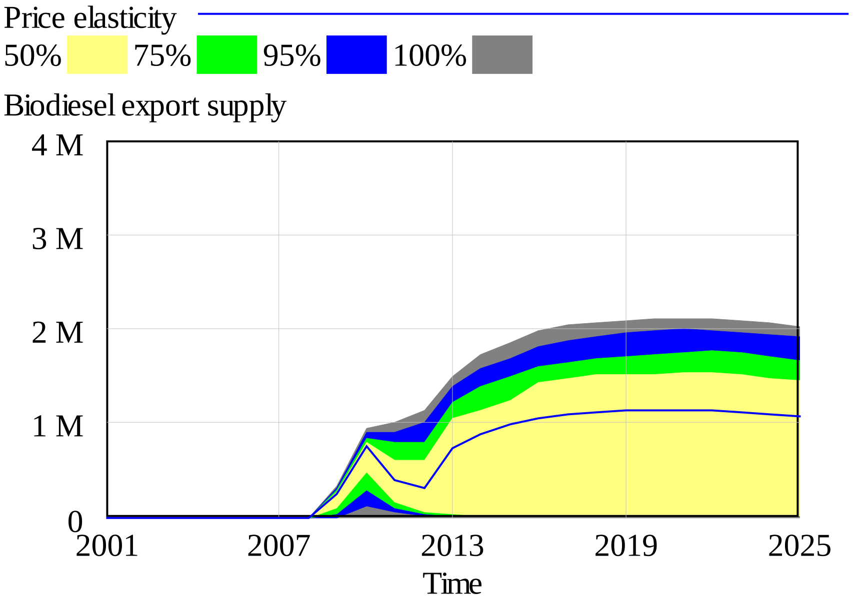

Figure 9-14. Biodiesel export supply: MVSS for net return elasticities.

The second set of elasticity values concern land supply and land transformation elasticities for each managed land-use type in the simulation model. Figure 9-15 show the MVSS results for soybean land supply. Simulations show that given the random uniform distribution functions for land supply and transformation elasticity values, land supply for soybean can vary in the range of 12-33 Mha/year at the end of the simulation period. Note that, depending on the elasticity values land supply for soybean cultivation can increase or decrease over time.

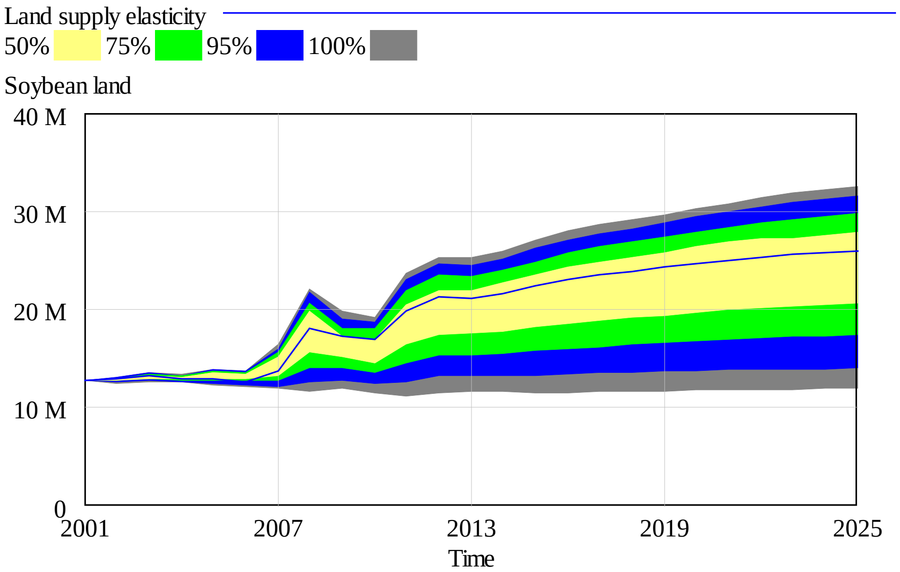

Figure 9-15. Land supply: MVSS for land supply elasticities.

9.8. List of experts

Table 9-20. List of experts.

Name	Institution	Issue
Andres Leone, Miguel Almada	Ministerio de Agricultura, Ganadería, Pesca y Alimentos (MAGPyA)	Biodiesel policy
Carlos St. Jaimes	Cámara Argentina de Energías Renovables (CADER)	Biodiesel market and policy
Claudio Molina	Asociación Argentina de Biocombustibles e Hidrogeno (AABH)	Biodiesel market
Federico Pochat	Cámara Argentina de Biocombustibles (CARBIO)	Biodiesel market
Patricia Bergero	Bolsa de Comercio Rosario (BCR)	Soybean, oil and meal markets
Miguel Calvo	Asociación de la Cadena de la Soja de Argentina (ACSOJA)	Soybean production
Ricardo Negri, Gabriel Vazquez	Consorcios Regionales de Experimentación Agrícola (CREA)	Soybean production
Guillermo Prone	Asociación de la Cadena de la Soja de Argentina (ACSOJA)	Soybean production
Martin Fraguio	Asociación Maíz Argentino (MAIZAR)	Soybean production
Juliana Albertengo	Asociación Argentina de Productores en Siembra Directa (AAPRESID)	No-tillage farming
Ignacio Gasparri	Laboratorio de Investigaciones Ecológicas de las Yungas – Universidad Nacional de Tucumán (LIEY-UNT)	Land-use change
Stella Carballo, Noelia Flores Marco, Alicia Anschau	Instituto Clima y Agua - INTA	Spatial data, land-use change
Jorge Hilbert, Luciana Moltoni	Instituto de Ingeniería Rural – Instituto Nacional de Tecnología Agropecuaria (IIR-INTA)	Biodiesel LCA

10. Curriculum vitae

Luis Panichelli

Born 15 March, 1980
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Education

2006 MAS in Environmental Management of Farming Activities (UBA, Buenos Aires, Argentina).
Project: Life Cycle Assessment of soybean-based biodiesel production in Argentina.

2003 Environmental Engineering Degree (UCA, Buenos Aires, Argentina)

Actual position

2007- EPFL- BPE (Swiss Federal Institute of Technology Lausanne- Bioenergy and Energy Planning Research Group), Lausanne, Switzerland
Research Assistant- PhD Candidate, Environment Program
Thesis: Biofuels' policies, land-use change and GHG emissions. Methodological framework and system dynamics modeling. Application to soybean based biodiesel production in Argentina

Previous positions

2005-2007 EPFL- LASEN (Swiss Federal Institute of Technology Lausanne- Laboratory of Energetic Systems), Lausanne, Switzerland
Assistant- Suisse Confederation Scholarship Holder
Project: Biomass-to-Energy Logistics: Forest residues and optimal facilities location in Northern Spain.

2004- 2005 INTA- IIR (National Institute of Agricultural Technology- Rural Engineering Institute), Buenos Aires, Argentine
Research Assistant
Project: Biofuels and Anaerobic Digestion of Organic Solid Wastes.

2004 IBERPAC (Environmental Consultancy), Buenos Aires, Argentine
Consultant
Project: Environmental and Quality Management Systems implementation in Municipal Solid Wastes treatment companies.

2003 La Salle University- Agro-Business Faculty, Bogotá, Colombia
Research Assistant
Project: Alternatives to Improve Solid Waste Management in tropical fruit farm, Sasaima, Colombia.

2002 – 2003 INTECH – IIB (Chascomus Institute of Technology – Institute of Biotechnology Research), Chascomus, Argentina
Research Assistant (Major final work)

Project: Utilisation of brewery wastes to produce edible mushroom Pleurotus Ostreatus.

Languages and technical skills

Languages: Spanish: Native, English: Fluent, French: Fluent, Italian: Intermediate, Portuguese: Intermediate
Computer skills: Microsoft Office, Vensim (System Dynamics Software). ArcGis (GIS software), Simapro (LCA software)

Obtained research grants

2005 CFBE (Federal Commission for Scholarships for foreign students) Switzerland
2005 INTA (National Institute of Agricultural Technology), Argentina
2003 IAESTE (International Association for the Exchange of Students for Technical Experience), Colombia

Patents

Patent N° AR 030101650 Substrates compositions for edible mushrooms growing that allowed the utilisation of brewery spent grains from brewing industries. INTECH-CONICET.

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A. Angeli-Dimakis, M. Biberacher, J. Dominguez, G. Fiorese, S. Gadocha, E. Gnansounou, G. Guariso, A. Kartadilis, L. Panichelli, I. Pinedo, and M. Robba. Methods and tools to evaluate the availability of renewable energy sources. *Renewable and Sustainable Energy Reviews*, 2010.

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Panichelli L., 2007. ¿Cómo se relaciona el Análisis de Ciclo de Vida (ACV) con los biocombustibles? Boletin Iram, Octubre 2007.

Panichelli L., 2007. Certificación de producción sustentable de biocombustibles: Consecuencias para la Argentina. Magazine ‘Agromercado’; October 2007. (270).