Estimating greenhouse gas emissions from indirect land-use change in biofuels production: concepts and exploratory analysis for soybean-based biodiesel production

Luis Panichelli and Edgard Gnansounou*
Laboratory of Energy Systems, Ecole Polytechnique Fédérale de Lausanne, (CH)

Increased demand for biofuels in order to partially substitute fossil fuels in different parts of the world will require the use of a significant amount of biomass. Energy crops production on current land and use of biomass in a given region can induce displacement of activities and land-use changes elsewhere. This effect is known as indirect land-use change (ILUC). Due to changes in the carbon stock of the soil and the biomass, ILUC has consequences on the GHG balance of a biofuel that are not presently considered in the evaluation of the environmental merits of biofuels. Significant changes in land-use are expected to occur in biofuel producing countries and their consequences may affect global markets. This paper aims to 1) review the state-of-the-art for accounting for indirect effects in biofuels production and their influence on the greenhouse gas balance of a biofuel pathway, 2) present a model to estimate and optimize GHG emissions from LUC and 3) estimate potential GHG emissions for the case of soybean-based biodiesel production, as an example. ILUC concepts and a classification of ILUC sources are proposed. Then a methodological framework to quantify GHG emissions is discussed and applied to the case study. Different scenarios to achieve the demand are proposed and their implications related to the ILUC are determined. Using a system-wide approach and a non-linear programming (NLP) model, the GHG emissions are evaluated in terms of carbon pay back time and optimized based on the soybean supply strategy to produce biodiesel.

Keywords: indirect land-use change (ILUC), greenhouse gas (GHG) emissions, biodiesel, optimization

Introduction

Greenhouse gas (GHG) emissions reduction is one of the main drivers of biofuels development. However, this assumed benefit is now under discussion, especially due to emissions from land-use change (LUC) [1, 2, 3]. Therefore some countries and regions worldwide being experienced biofuels blending policies (e.g. the EU [4], the UK [5], Switzerland [6], the Netherlands [7], State of California in the US [8]) have defined a carbon conservation criterion (i.e. an emissions reduction target) that must be fulfilled in order to trade and supply biofuels. Thus biofuel importing countries should select production regions that satisfy this criterion.

From the point of view of a biofuel producing country willing to export, it is crucial to plan how and where the biofuel feedstock will be produced based on the available production options. However, this is not straightforward as the feedstock production may be subject to constraints that will limit the capacity of production under each option. The chosen combination of production options to satisfy a given demand of biofuels is the result of a multi-criteria decision based on economical, political, technological, agro-ecological, social and environmental factors, which determined the local framework for biofuels production. This decision will have an impact on LUC, and therefore on the GHG emissions balance of the biofuel. Consequently, reducing GHG emissions from direct (DLUC) and indirect LUC (ILUC) is a key element to optimize the environmental performance of a given biofuel pathway.

Planning biofuels production requires international consensus to find global sustainable strategies that minimize ILUC effects. Such a process may include three steps: first, each producing country has to define its local framework and its best strategy assuming that the other countries are followers; second, taking into account the magnitude of impacts, a negotiation may take place in order to find global international strategies; third, guidelines and sustainability standards could finally be defined and implemented in order to internationally promote the most sustainable strategies.

In the framework of the first step, this paper discusses ILUC, based on several aspects i.e. land-use concepts, classification of ILUC sources, influence of ILUC on GHG emissions balance of biofuels, and current approaches to quantify this effect. Then a constrained non-linear programming (NLP) model is proposed to estimate the carbon pay-back time (CPBT) of a given biofuel production strategy with respect to dimensions such as the biofuel origin, the

* Author for correspondance
E-mail : edgard.gnansounou@epfl.ch

Modified version published in: Journal of Scientific & Industrial Research, Vol. 67, Nov. 2008, pp. 1017-1030
Received 15 July 2008; revised 05 September 2008; accepted 03 October 2008

type of feedstock, the feedstock production strategy, the displaced activities relocation strategy and the type of land-use where activities are relocated. The model allows evaluating the impact of a chose strategy on the GHG emissions from ILUC. The model is finally illustrated by a hypothetical case of a soybean-based biodiesel producing and net exporting country with a biodiesel blending obligation. The tool is intended for policy-makers in a given country willing to plan their biofuel production strategy. The global solution will then be determined by a negotiation process between the optimal strategies for each country.

The concept of indirect land-use change

Land-use concepts

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) [9], including forestland, cropland, grassland, wetlands, settlements and other land.

Direct land-use change 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 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 [10].

The use of feedstock for biofuels production can generate the conversion of uncultivated land (e.g. set-aside, fallow, forest), the shift of previous uses of the biomass (e.g. construction, crafting, animal feed, food) and the shift of previous activity in a territory (e.g. cattle, food crops). These displaced activities and uses of the biomass will increase pressure on land in countries where there is a shortfall of agricultural land. On the other hand, biofuels production will also increase the availability of co-products. Using co-products to feed animal may reduce agricultural pressure for animal feedstock production. This LUC avoided by the co-product can be considered as a credit for the biofuel pathway.

Indirect land-use change is characterized as a spatial-temporal market driven process with a global scope. Relocation of displacements will depend on the demand for the displaced products and the available feedstock to achieve a given demand. These factors are dependent mainly on market prices of displaced products, which will be relocated worldwide between producing countries of the same product. Spatial distribution of raw materials to produce displaced products will be determined by location factors. These factors are bio-physical characteristics within each producing country (and even agro-ecological zones) that do not depend on global markets [11]. Moreover, land-use in a given location is a dynamic process. The land-use can change based on owners decisions and a chronological sequence of successive land-uses is obtained. A global economic approach is needed to account for the market driven process and the worldwide land-use interactions. Down-scaling these effects require space-time modeling to account for geographical and temporal dependence of LUC.

Impact of ILUC on GHG emissions

GHG emissions from ILUC are claimed to be even more important than emissions from DLUC [10]. Despite the high inaccuracy, some authors have produced a range of values to show the magnitude of this effect.

Farrel and O’Hare [12] have made rough estimations of ILUC GHG emissions driven by biofuels demand in the United States (US), concluding that if temperate grasslands and tropical forests are converted to croplands, the GHG emissions of most biofuels pathways are higher than those of the fossil reference.

Searchinger *et al.* [3] have studied the impact of including direct and indirect LUC GHG emissions in the life-cycle assessment (LCA) of corn-based ethanol in the US, stating that US corn production for ethanol will generate GHG emission for a period of 167 years (CPBT) until emissions from LUC can be balanced with the benefit from substituting fossil fuel.

Notwithstanding, LUC do not imply necessarily a negative effect. Conversion of forest, wetlands and grasslands to cropland usually results in a net carbon emission. However, cropland established on previously sparsely vegetated, highly disturbed lands and some grasslands can result in a net gain in both biomass and soil carbon. Moving from a long-term (20 yr) cultivated system to a shifting cultivation system increases carbon stock in soils. However, changes in the carbon stock can also take place even if the land-use does not change (e.g. cropland remaining cropland) [9]. Good management practices in a field, such as reduced tillage, leaving crop residues at place and increasing external input of organic matter, contributes to carbon stock improvement. Agronomic research is being conducted in this sense to propose mixed production systems (e.g. intersowing, degraded pastures replacement by an intensive crop/pasture system) [13]. EU governments recommend using idle land for biofuels production in order to avoid indirect effects [14].

Definition and classification of indirect land-use sources

ILUC sources can be classified by the type of displacement [15], as follows:

Spatial ILUC: Displacement of prior production to other location

Spatial ILUC occurs when the production of crops for biofuels in a land pushes the previous activity to another location. The use of the new location to place the previous activity generates a LUC attributable to the implantation of the biofuel crop on that land (e.g. replacing pastureland for energy crops may induce deforestation elsewhere to place pastureland).

Use ILUC: Shifting biomass use in the same location

Use ILUC occurs when the land-use in a location remains the same but the production is used for another purpose pushing the production for the previous purpose to another land. The introduction of a new demand for the same feedstock has caused the expansion of plantations. This expansion is considered as an indirect effect of shifting the biomass use. However, DLUC from crops expansion for biofuels production can be overlapped with ILUC from shifting biomass use. If the biomass use remains the same (ILUC is avoided), new plantations will be used to produce biofuels. Consequently, avoiding changes in biomass-use will result in DLUC to produce energy crops.

Displaced activity/use ILUC: Shifting previous activity to another country

Displaced activity ILUC refers to DLUC occurring in another country due to the shifting of the displaced activity, e.g. pasture area expansion in B due to pasture displacement in A. This DLUC in B can be attributed to biofuel feedstock expansion in A. The same applies when the biomass use is substituted, e.g. changing corn use from animal feed to ethanol may induce production increments in other corn producing countries. The situation where crops rotation in a land is substituted by a monoculture also applies here, e.g. shifting corn-soybean rotation to corn may displace soybean production to another soybean producing country.

Evaluating the effects of ILUC

Quantification of ILUC is characterized at present by an economic modeling of demand for land in a general/partial equilibrium model. Global ILUC is modeled by relocation of activities on a worldwide scale, based on worst case assumptions (i.e. deforestation). Choice of land where to allocate displaced activities is subjectively based on historical LUC data. Relocation is restricted to cropland (i.e. pasture displacement is not considered). ILUC is restricted to biomass-use substitution and decreased crop rotation and is modeled as decreased supply in producing country/increased production in another producing country of the same product.

General scientific consensus exists about using an economic approach to address indirect effects. Available studies use general/partial equilibrium models [16, 17]. The only confirmed hypothesis is that ILUC occur. However, at present, only rough estimations based on hypothetical cases are available. These estimations give a range of values that shows the magnitude of the effect, and focusing primarily on negative impacts (i.e. deforestation). No model has been developed or used, according to our knowledge, to down-scale indirect effects lower than the national level and neither to predict the spatial relocation of displaced activities.

The FAPRI international model [18] was used to relocate displaced corn production for other purposes and soybean displaced from avoided rotation on the same land [3, 19]. Converted land is assigned based on the proportion of land that has been transformed into cropland in the past and no modeling of the spatial allocation of indirect effects was done. Cropland conversion in other countries due to US ethanol production is quantified and LUC emissions for each region are estimated. This data is used as input for the GREET model [20] to calculate the GHG balance of US corn-based ethanol production for fuel use.

The GTAP model [21] was used to evaluate LUC due to crops consumption [22]. ILUC for a given crop is modeled as expansion and intensification processes, assuming crop displacement as an intermediate state to a new general equilibrium. Main focus is in modeling of the intensification process. An application of the approach to wheat consumption in Brazil, China, Denmark and US is under development [23].

A first attempt to account for the spatial distribution of LUC due to biofuel crops was developed by linking the LEITAP [24] (a modified version of GTAP), the IMPAGE [25] and the Dyna-CLUE models [26]. The integrated model allows making a spatial explicit, multi-scale, quantitative description of LUC through the determination of location factors based on present land-use structure. The approach allows determining explicitly the location of crops expansion and consequently, the direct land-use effects of biofuels. The model was applied to biodiesel and bioethanol production in the European context [27]. ILUC is assumed to occur, but not addressed.

Due to the nature of ILUC, a systemic approach should be applied to fully account for this effect. Several authors have applied the so called "Consequential LCA" (CLCA) to evaluate the changes produced in a system as a consequence of a decision. The CLCA is based on a system-wide approach where system boundaries are expanded to consider the impact on the affected activities, and is therefore appropriate to study ILUC. At present, CLCA was the adopted methodology to assess ILUC in biofuels production. It has been applied to study ILUC of corn production for ethanol in the US [28] and to estimate ILUC due to crops consumption [22].

GHG emissions from ILUC

Problem formulation

In order to meet a given demand of biofuel (BD_T), either for domestic consumption or export, a certain country can choose between importing the biofuel, domestically produce it or both in a given proportion (Eq. 1). This biofuel can be produced from a variety of feedstocks (f) (Eq. 2) and the required quantities ($F_{Do,f}$) depend on conversion yields ($y_{c_{o,f}}$) of each feedstock in each originating country (o) (Eq. 3). The required feedstock quantity (F_{Pi}) to achieve demand can be as well obtained by a diversity of feedstock production options (i) (Eq. 4) e.g a) biomass-use substitution, b) crop area expansion, c) yield improvement on the same land, d) shortening of rotation period and e) intensification by intercropping methods. Apart from options c) and e), all the other strategies may result in ILUC. In the first case, this occurs due to decreasing feedstock quantities for other purposes and compensating this reduction by producing the same amount elsewhere. This fact may have consequences on land-use dynamics in other producing regions and even in the same region. Option b) may result in LUC due to the replacement of existing activities on another land, and option d) will result in reducing the production of the rotation crop or pasture and consequently may imply its relocation elsewhere.

The magnitude of these impacts will depend on how and where the displaced productions (D_{Pi}) are relocated. Each D_{Pi} depends on the feedstock and the displaced product yields ($y_{o,f}, y_{o,d}$) (Eq. 5). The relocation of displaced production can take place in the region or elsewhere and can be achieved by a variety of supply strategies (s) such as intensification, decrease crops rotation or extensification (Eq. 6), similar to the feedstock production options, and consequently may lead again to LUC. The DLUC (i.e. from crop area expansion) resulting from these relocations constitute an ILUC attributed to biofuels production. The displaced activities can also be partially relocated or not relocated at all, which means that no LUC occurs but also that the product is no longer available.

The changed area will be distributed between different land-uses (k) (e.g. forest, grassland, cropland) (Eq. 7). The area needed to produce the displaced production is a function of the displaced production and the yield of the displaced product (Eq. 8). Finally, from equations 1 to 8, the area change to relocate each displaced activity ($S_{o,f,i,s,k}$) (Eq. 9) will be a function of the total biofuel demand, the feedstock yield, the conversion yield and five distribution factors that determine the part of the biofuel demand that is satisfied from each biofuel origin (α_o), each feedstock ($\beta_{o,f}$), each feedstock production strategy ($\chi_{o,f,i}$), each displacement supply strategy ($\delta_{o,f,i,s}$) and each land-use ($\varepsilon_{o,f,i,s,k}$). Each factor depends on the previous one. Given a specific biofuel demand and a defined feedstock and conversion yield, the area needed to produce the displaced activities will be a function of the distribution factors. The maximal distribution for each factor is determined by optimizing an objective function with respect to constraints that are exogenously defined. The resulting GHG emission from each LUC ($e_{LUCo,f,i,s,k}$) will depend on the carbon stock change between land-uses (e_k), the changed area of each land-use ($S_{o,f,i,s,k}$) and the period during which that land will be used to produce biofuel feedstock (ρ) (Eq. 10). The carbon pay-pack time (CPBT) is then expressed as the ratio between the total carbon stock change from direct and indirect land-use change during the biofuel demand period (from equations 7 and 8) and the amount of carbon that is saved annually by substituting the fossil fuel by the biofuel (ΔCI_{fuel}) (Eq. 11-12). An allocation factor (a_{bio}) and a fuel economy factor (c_{bio}) are introduced to allocate LUC GHG emissions to the biofuel and to express emission per km, respectively. a_{bio} depends on the allocation of co-products. c_{bio}

depends on the lower heating value of the biofuel and the kilometric biofuel consumption.

$$BD_o = \alpha_o \cdot BD_T \tag{1}$$

$$BD_{o,f} = \beta_{o,f} \cdot BD_o \tag*{2)}$$

$$F_{D\,o,f} = \frac{BD_{o,f}}{yc_{o,f}} \tag{3}$$

$$F_{Pi} = \chi_{o,f,i} \cdot F_{D\,o,f} \tag{4}$$

$$D_{Pi} = \frac{y_{o,d}}{y_{o,f}} \cdot F_{Pi} \tag{5}$$

$$D_{Ps} = \delta_{o,f,i,s} \cdot D_{Pi} \tag{6}$$

$$D_{Pk} = \varepsilon_{o,f,i,s,k} \cdot D_{Ps} \tag{7}$$

$$S_{o,f,i,s,k} = \frac{D_{Pk}}{y_{o,d}} \tag{8}$$

$$S_{o,f,i,s,k} = \alpha_o \cdot \beta_{o,f} \cdot \chi_{o,f,i} \cdot \delta_{o,f,i,s} \cdot \varepsilon_{o,f,i,s,k} \cdot \frac{BD_T}{y_{o,f} \cdot yc_{o,f}} \tag{9}$$

$$e_{LUC\,o,f,i,s,k} = S_{o,f,i,s,k} \cdot e_k \cdot \rho \tag{10}$$

$$CPBT = \frac{\sum_{k=1}^{K} \frac{e_{LUC\,o,f,i,s,k}}{BD_T} \cdot \frac{a_{bio}}{c_{bio}}}{\Delta CI_{fuel}} \tag{11}$$

$$\Delta CI_{fuel} = CI_{fossil} - CI_{bio} \tag{12}$$

Optimization

The reduction of GHG emissions from LUC is done through the minimization of the carbon pay-back time (CPBT) of the biofuel production (Eq. 13).

$$CPBT(\min) = \frac{\sum_{k=1}^{K} \alpha_o \cdot \beta_{o,f} \cdot \chi_{o,f,i} \cdot \delta_{o,f,i,s} \cdot \varepsilon_{o,f,i,s,k} \cdot \frac{e_k \cdot \rho}{y_{o,f} \cdot yc_{o,f}} \cdot \frac{a_{bio}}{c_{bio}}}{\Delta CI_{fuel}} \tag{13}$$

The independent variables are the respective distribution factors, namely α_o, $\beta_{o,f}$, $\chi_{o,f,i}$, $\delta_{o,f,i,s}$ and $\varepsilon_{o,f,i,s,k}$. The optimization constraints accounts for:

i) Non-negativity and maximum constraint

Each distribution factor (variables) should be lower than a specified maximum (M) percentage and non-negative. Each maximum is exogenously determined by a multi-criteria process (Eq. 14-18).

$$0 \le \alpha \le \alpha_M \quad \text{for each } \alpha \tag{14}$$

$$0 \le \beta \le \beta_M \quad \text{for each } \beta \tag{15}$$

$$0 \le \chi \le \chi_M \quad \text{for each } \chi \tag{16}$$

$$0 \le \delta \le \delta_M \quad \text{for each } \delta \tag{17}$$

$$0 \le \varepsilon \le \varepsilon_M \quad \text{for each } \varepsilon \tag{18}$$

ii) Production constraint:

The required feedstock to achieve the biofuel demand (F_D) is equal to the feedstock produced (F_P) (Eq. 19).

$$F_D = F_P \tag{19}$$

iii) Land availability constraint

The available land to produce the biofuel feedstock should not be higher than the total feedstock area (Eq. 20).

$$S_{f\,bio} \le S_{fT} \tag{20}$$

iv) Distribution constraint

For each o, each f, each i, each s and each k the sum of the percentages should be equal to 100% (Eq. 21-25). That is, the biofuel demand is totally satisfied and the displaced production is fully relocated.

$$\sum_{o=1}^{O} \alpha_o = 100 \tag{21}$$

$$\sum_{f=1}^{F} \beta_{o,f} = 100 \text{ for each } o \tag{22}$$

$$\sum_{f=1}^{F} \chi_{o,f,i} = 100 \text{ for each } o \text{ and } f \tag{23}$$

$$\sum_{s=1}^{S} \delta_{o,f,i,s} = 100 \text{ for each } i,\ f \text{ and } o \tag{24}$$

$$\sum_{k=1}^{K} \varepsilon_{o,f,i,s,k} = 100 \text{ for each } s,\ i,\ f \text{ and } o \tag{25}$$

Case study: soybean-based biodiesel production

Context definition

The following example depicts the potential origin of indirect emissions (Fig. 1). It illustrates the hypothetical impact of soybean-based biodiesel production in a country A, and the resulting ILUC in that country and elsewhere (countries B and C). The example is not exhaustive but shows potential pathways on a worldwide scale. The country A is a biodiesel producing and net exporting country with a mandatory blending target. The projected scenario for 2020 states a 20% blending of biodiesel in fossil diesel and a 30% increment of biodiesel exports, which means a total production increment of 12.8 Mtons of biodiesel from 2008 to 2020. The country A can partly import soybean-based biodiesel from country C (which is a leading biodiesel producer and exporter) or nationally produce it using soybean as feedstock. The required soybean demand for biodiesel can be satisfied by a) shifting previous use of soybeans, b) increasing yield, c) expanding crop area, d) decreasing rotation period with other crops/pastures and e) intersowing soybeans with other crops/pastures.

Two use-shift strategies are considered based on exports reduction of soybeans and soybean oil. The first strategy consists in diverting part of soybean export to increase domestic use of produced oil for biodiesel, the supplementary meal being exported as animal feedstock. Decreasing soybean export will stimulate other soybean producing countries to increase their production. We assume this demand is totally absorbed by B, which is a leading soybean producer and exporter. The new soybean demand in B can be achieved by crop area expansion, intensification (yield increment, intersowing) or decreasing crops rotation. Extensification will result in forest, grassland and pasture conversion in B. Surplus soybean meal production will decrease other feedstock production for animal feeding. Avoided corn expansion in B (which is a leading corn producer and exporter) for animal feedstock was estimated based on the protein content of soybean meal and corn, respectively. This avoided land-use conversion is accounted as a credit for soybean-based biodiesel produced in A.

The second shift-use strategy consists in reducing oil exports and using this oil to produce biodiesel, while keeping stable soybean exports. This will stimulate vegetable oil producers to expand production. We assume no substitution between vegetable oils (e.g. palm, sunflower, cotton, peanut, rape) because of consumer preferences for a specific type of oil. Consequently, soybean oil producers are assumed to increase production to supply the displaced oil. We assume the displaced oil production is totally absorbed by C (which is a leading soybean oil producer and exporter). Soybean for oil production in C will be achieved by extensification, intensification or rotation processes. Extensification will cause forest, grassland and pasture conversion in C.

Soybean yields in A will be increased from 2.54 t/ha in 2008 to 3.5 t/ha in 2020. This can be achieved with e.g. new agricultural management practices (e.g. high technology agriculture), new crop varieties, increased use of fertilizers and pesticide. Yield improvement will avoid crop area expansion in A and consequently land-use changes.

Soybean production in A will partially expand into fallow land, cropland, pastureland, grassland and forest. When expanding into fallow land, forest and non-productive grassland, indirect effects are avoided. However, GHG emissions from this DLUC are accounted for. When expanding into pastureland or cropland, the relocation of these activities results in LUC in A. If the demand for these land-uses does not decrease, displaced crops and pastureland are assumed to expand into grassland and forests or absorbed by intensification processes (improved pastures, mixed systems of crop-pasture, intercropping). When intensification occurs, no indirect effects are assumed.

Part of soybean production is done in rotation with other crops and pastures, mainly corn. Soybean can be produced as monoculture by substituting corn-soybean rotation. If demand for corn does not decrease, corn production will be relocated in B. If intensified, no LUC will occur. We assumed that 30% of the corn demand is covered by yield increment [29]. If corn area expansion occurs, this is assumed to be produced in B. When fallow land is used, no indirect effects occur.

Intersowing systems allows producing two crops simultaneously on the same land. Soybean can be simultaneously produced with other crops and pastures (e.g. wheat, corn and sunflower and pastures such as millet and *Brachiaria* spp). Even though the technology is in development stage, we assume that its adoption may be significant by 2020.

Biodiesel imports are assumed to come from C, where the feedstock is soybean produced either by intensification, decreased crops rotation or extensification. In case of crop expansion, this will occur into cropland, grassland or forest, leading to DLUC. This land conversion is an ILUC for the biofuel strategy in A.

Model development and data used

The model was described as a non-linear programming (NLP) optimization problem, with 23 independent variables, and 66 constraints. All the variables are continuous and expressed as percentages (%). The model was developed in a Microsoft Excel® platform and the problem is solved using the Solver function. The Microsoft Excel Solver tool uses the Generalized Reduced Gradient (GRG2) non-linear optimization algorithm.

The data inputs to the model are presented in Table 1. A baseline was constructed for the year 2008 and then a projection to 2020 was defined. The data, mainly taken from the three main soybean producers in the world (i.e. Brazil, United States and Argentina) was complemented with assumed default values. GHG emissions from LUC account for carbon stock changes in soil, in biomass and in dead organic matter. Crop and conversion yields, carbon stock changes, and land-uses were the default values of the UK Renewable Fuel Agency (RFA) Carbon Calculator [30], used to estimate the carbon intensity of traded biofuels in the UK (including DLUC) [31]. However, due to lack of data, many assumptions have been done by the LASEN (Table 2).

Results

The results of the CPBT calculation are presented in Table 3. Results are shown not only for the minimization of the function (best strategy to reduce GHG emissions from LUC) but also for the maximization of the function (maximum GHG emissions from LUC to produce the required biodiesel). The minimum and maximum CPBT are the bounds of the CPBT, which means that any strategy adopted by A to produce the biofuels' demand, and subject to the specified constraints, will result in a CPBT value that will be between these boundaries. The minimum bound is -46 years, i.e. the biofuel strategy is an effective option to mitigate global warming. This strategy consists in avoiding shifting of soybean oil exports, yield increments and avoiding soybean expansion in A. So, the soybean strategy to produce 79.4 Mt of soybean (12.8 Mt of biodiesel) is composed by soybean exports shifting (30%), by importing soybean-based biodiesel (30%), by soybean production by intersowing (21%) and by decreasing rotation with corn (11%) (Table 4). The strategy avoids extensification as soybean production shifted to B from exports is absorbed by intensification and crops rotation. LUC in B from decreasing corn rotation and LUC in C for soybean production as feedstock for biodiesel are avoided by intensification and crops rotation as well. A credit is also accounted for avoided corn area expansion in B due to increase soybean meal production in A for animal feedstock. Consequently, the system reduces GHG emissions from LUC by 150 Mt CO_{2eq} (Table 4).

On the contrary, when maximizing the function a value of 979 years is obtained, which means that the biodiesel should be produce for a period of 979 years until the emissions from LUC can be balanced by the benefit obtained from substituting fossil diesel by biodiesel. In this case, the strategy to produce the same quantity of soybeans consists in producing soybeans by shifting soybean and soybean oil exports (30% and 11%, respectively), by biodiesel imports (24%), by crop area expansion (20%) and by intersowing (3%), avoiding decreasing rotation and yield improvement. However, under this strategy, LUC is not avoided. Direct and indirect land-use changes result from the relocation of activities mainly by extensification into forest and pastureland. Consequently, GHG emissions from LUC to produce the required demand of biodiesel increase to 3272 Mt CO_{2eq} (Table 4).

According to the Renewable Transport Fuel Obligation (RTFO) of the UK government [5], biofuel feedstock production should not cause DLUC with a carbon pay-back time exceeding 10 years. Based on this principle we expand the limit to 20 years but including as well the ILUC. Many solutions to obtain a CPBT of 20 years can be obtained; here, we show only one, chosen randomly. Results are shown in Tables 3 and 4.

Discussion

Model assumptions and limitations

The model allows to find the boundaries for the GHG emissions from LUC of a given feedstock production strategy to meet a given biofuel demand. Knowing the CPBT of a production strategy allows planning how to produce the required biofuel feedstock for export, by fulfilling international biofuel standards on carbon preservation. However, a biofuel production strategy depends on many factors, and so this dimension should be included as a criterion in a multi-criteria decision process.

The model is very sensible to the constraints, e.g. when no biodiesel imports are allowed, the minimum CPBT increase to -32 years; when no intensification is allowed, the model found no solution. This highlights the significance of the constraints in finding a feasible solution and states the need for a specific determination of the constraints' values. For the case study illustration, these values were fixed exogenously and somehow randomly. When applied to a real case, specific attention should be put in defining these values as accurately as possible. Constraints depend on political, social, economical, environmental, technological, strategic and agro-ecological factors and so, a multi-criteria method should be applied to determine them. General equilibrium models, e.g. GTAP, allow managing these factors in a certain extent based on an econometric approach. Moreover, GIS based models can be applied for downscaling and defining spatial-temporal dependent constraints and boundaries. The integration of these tools can give a realistic estimation of the system boundaries.

Determining LUC in other countries due to biofuel production in a given country is not straightforward, e.g. determining how decreasing corn rotation area in A to produce energy crops has induced corn area expansion in B. First, because no model exists to determine which land-uses in other countries have changed due to the relocation of displacements, Secondly, because it is doubtful whether we should penalize biofuels production in a country with effects that are occurring elsewhere as a consequence of political and economical decisions in those countries. However, as stated, at this stage it seems that even if these effects should be known and a causal relationship should be established, the consequences (GHG emissions) are particularly difficult to be accurately attributed to the expansion of biofuels production in a given country and consequently it would be delicate to include them in the GHG emissions balance at a country level. Moreover, the inclusion or not of these emissions depends on the stakeholders. From a political and strategically point of view, in order to estimate at a global scale the effects of biofuels introduction these emissions should be taken into account. In order to simplify the illustrated example, several aspects have not been considered.

Policy-makers at the country level do not have control over ILUC occurring in other countries. Consequently, feedstock production options can be constrained to avoid biofuel imports and shifting exports if ILUC in other countries are proven highly negative. On the other hand, the tool can be useful to develop a supra-national biofuel strategy that is the optimal for biofuel producing and consuming countries and those affected by ILUC. This will require the integration of biofuel production strategies in other countries (e.g. B and C).

Actually, the strategies are not always independent from each other contrary to what is considered in the illustration. For example, the yield increment strategy is modeled separately. Notwithstanding, the increased productivity should be distributed between the other strategies, in order to account for the simultaneous effect of crop expansion and yield increment during time.

The optimization is static. In order to account for system dynamics, an annual based simulation should be performed.

The model corresponds to a hypothetical case constructed on the basis of the three main soybean producers in the world.

Case study results

For model simplification, we have assumed that the displaced productions are fully relocated only in one country, no substitution of vegetable oils occurs, only three land-uses, only one origin for biofuel imports and only one case of crops rotation are considered. However, the model can be expanded to account for as many as feasible interactions as required. But this will increase the computable time to solve the optimization problem as the number of variables and constraints will be increased as well. The application of such a model applied to a real case will depend on the development of a global economic and georeferenced database [32].

Decreasing corn rotation in A may lead to indirect effects elsewhere. These indirect effects are directly related to the production of biodiesel. On the other hand, even though decreasing crops rotation as a supply strategy to relocate displaced production may also lead to other displacement, this indirect effect is not accounted for. Indirect effects elsewhere are second order indirect effects for the case study. If included, this will result in a sequence of displacements until the displaced production is relocated in a natural biome/unused land or absorbed by intensification [22]. We have limited the system boundaries to first order ILUC.

LUC GHG emissions minimization avoids yield improvement. This is because in the best case (CPBT minimization) shifting exports accounts for a credit for avoided corn expansion for animal feed production; soybean-based biodiesel produced in C has a bigger ΔCI_{fuel} than biodiesel produced in A, and soybean yield in intersowing is higher than the yield improvement.

Biodiesel import is a main strategy for CBPT optimization. Consequently, the key factor is how the soybean for biodiesel in C has been produced (e.g. by expansion into forest or by intensification).

ILUC pathways were based on main interactions (i.e. main soybean and oil producers, main corn producers, main rotation crops), due to data availability. However, when modelling a real case, these pathways should be defined from the outputs of a global macro-economic model, the available options for feedstock and displaced products production and georeferenced data on land-uses.

The model is based on three land-use types (i.e. cropland, grassland and forest). But, it can be expanded to account for a more refined categorization of land uses, based on management practices and inputs level. Here we assumed zero LUC GHG emissions for cropland remaining cropland. This can be modified depending on data availability. Moreover, some LUC, such as cultivation on degraded land or mix crop/pasture systems can improve carbon stock. Consequently, accounting for these land-uses in the model will allow designing strategies for LUC GHG emissions mitigation.

Conclusion

Biofuels production as a strategy to mitigate global warming is currently under debate due to the influence of including direct and indirect land-use changes in the GHG balance of biofuels. All in all, LUC GHG emissions depend on how and where biofuels feedstock is produced. This choice depends on many decision factors and constraints. In order to test the effect of different feedstock production strategies on the GHG emissions balance of a biofuel, a non-linear programming model was developed. The model determines the boundaries of the CPBT for a given strategy and biofuel demand and finds the best combination of biofuel and feedstock production strategies to minimize GHG emissions for that country. Despite the model limitations, the tool is a first attempt to help decision-makers to strategize biofuels production in order to reduce GHG emissions on a global scale.

Nomenclature

o	Origin (region)	[ad]
f	Type of feedstock	[ad]
i	Feedstock production strategy	[ad]
s	Displaced production supply strategy	[ad]
k	Land-use change source	[ad]
d	Displaced product	
ρ	Period for which the carbon emissions are amortized (projection period)	[yr]
α_o	Percentage of biodiesel produced at each origin o	[%]
$\beta_{o,f}$	Percentage of biodiesel produced from each feedstock f	[%]
$\chi_{o,f,i}$	Percentage of feedstock produced under each production strategy i	[%]
$\delta_{o,f,i,s}$	Percentage of displaced production produced under each supply strategy s	[%]
$\varepsilon_{o,f,i,s,k}$	Percentage of extensified displaced production produced in each land-use k	[%]
$e_{LUC\,o,f,i,s,k}$	Carbon emissions from land-use change k produced by each o, f, i, and s during the projection period ρ	[CO_{2eq}]
a_{bio}	Biofuel allocation factor	[ad]
CI_{fossil}	Carbon intensity of fossil fuel	[t CO_{2eq}/km]
CI_{bio}	Carbon intensity of biofuel	[t CO_{2eq}/km]
c_{bio}	Fuel economy factor	[MJ/ km]
ΔCI_{fuel}	Carbon saved annually due to the fossil substitution by the biofuel	[t CO_{2eq}/km.yr]
BD_o	Amount of biofuel produced at each origin o	[t]
BD_T	Total biofuel demand	[t]
$BD_{o,f}$	Amount of biofuel produced from each feedstock f in each origin o	[t]
$yc_{o,f}$	Biofuel conversion yield for each o and f	[t_{bio} /t_f]
$F_{Do,\ f}$	Feedstock demand from each origin o	[t]
F_{Pi}	Feedstock production under each i	[t]
$y_{o,f}$	Feedstock yield	[t/ha]
D_{Pi}	Displaced production from each i	[t]
$S_{o,f,i,s,k}$	Area of the land-use change for each o, f, i, s and k	[ha]
e_k	Annual carbon emissions for each land-use k	[CO_{2eq}/ha.yr]
$y_{o,d}$	Yield of the displaced production	[t/ha]
D_{Ps}	Displaced production by each s	[t]
D_{Pk}	Displaced production relocated in each k	[t]
$CPBT$	Carbon pay-back time	[yr]

References

1. Fargione J, Hill J, Tilman D, Polasky S & Hawthorne P, Land Clearing and the Biofuel Carbon Debt, *Science Express*, Published online 7 February (2008), 10.1126/science.1152747.
2. Righelato R & Spracklen D V, Carbon Mitigation by Biofuels or by Saving and Restoring Forests?, *Science* 17, (317), no. 5840 (2007) 902.
3. Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D & Yu T, Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change, *Science* 319 no. 5867 (2008) 1238 – 1240.
4. Commission of the European Communities. *Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of renewable sources*. COM(2008) 19 final, 2008/0016 (COD) (2008).
5. Bauen A, Watson P & Howes J. *Carbon Reporting within the Renewable Transport Fuel: Methodology*. E4tech (2007).
6. Confédération Suisse, Administration fédérale des douanes. *Modification de la loi sur l'imposition des huiles minérales: Les grandes lignes*. DFF, AFD (2008).
7. Cramer J, et al. *Testing framework for sustainable biomass, Final report from the project group 'Sustainable production of biomass'*. Creative Energy (2007).
8. Farrell AE & Sperling D. *A Low-Carbon Fuel Standard for California, Parts 1 & 2*. University of California (2007)
9. IPCC, Good Practice Guidance for Land-use, Land-Use Change and Forestry, IPCC National Greenhouse Gas Inventories Programme (2006).
10. Turner B T, Plevin R J, Hare M & Farrell A, Creating markets for green biofuels: Measuring and improving environmental performance, Research report UCB-ITS-TSRC-RR-2007-1, University of California Berkeley, Transportation Sustainability Research Center, April, (2007).
11. Wassenaar T, Gerber P, Verburg P H, Rosales M, Ibrahim M & Steinfeld H, Projecting land use changes in the Neotropics: The geography of pasture expansion into forest, *J Global Environmental Change* 17 (2007) 86-104.
12. Farrell A E & O'Hare M, Greenhouse gas (GHG) emissions from indirect land use change (LUC), Memorandum for the California Air Resources Board, Energy & Resources Group, University of California Berkeley, (2008).
13. Cerri C E & Cerri C C, Biofuel Carbon Footprint : basis for a greenhouse gas emission reduction, Presentation at *Biofuels and Society Workshop*, 14 November (2007).
14. Schnepf R, European Union Biofuels Policy and Agriculture: An Overview, *CRS Report for Congress Resources*, Science, and Industry Division, Order Code RS22404, March 16, (2006).
15. Gnansounou E, Panichelli L, Dauriat A & Villegas J D, Accounting for indirect land-use changes in GHG balances of biofuels: Review of current approaches, Swiss Federal Institute of Technology of Lausanne, Laboratory of Energy Systems (LASEN), working paper, 437.101, (2008).
16. Ignaciuk A, Vohringer F, Ruijs A, & Van Ierland E C, Competition between biomass and food production in the presence of energy policies: a partial equilibrium analysis, *Energy Policy* 34 (10) (2006) 1127-1138.
17. Ignaciuk, A M & Dellink R B, Biomass and multi-product crops for agricultural and energy production: An AGE analysis, *Energy Economics* 28 (3) (2006) 308-325.
18. Food and Agricultural Policy Research Institute, FAPRI Agricultural model, http://www.fapri.iastate.edu/models/.
19. Tokgoz S, Elobeid A, Fabiosa J, Hayes D J, Babcock B A, Yu T, Dong F, Hart C E & Beghin J C, Emerging Biofuels: Outlook of Effects on U.S. Grain, Oilseed, and Livestock Markets, Staff Report 07-SR 101. May, (2007).
20. Argonne National Laboratory, The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, http://www.transportation.anl.gov/software/GREET/.
21. Department of Agricultural Economics, Purdue University, Global Trade Analysis Project (GTAP), https://www.gtap.agecon.purdue.edu/models/current.asp.
22. Kloverpris J, Wenzel H & Nielsen P H, Life Cycle Inventory Modelling of Land Induced by Crop Consumption, Part 1: Conceptual Analysis and Methodological Proposal, *Int J LCA* 13 (1) (2008) 13-21.
23. Kløverpris J, Baltzer K & Nielsen P H, Life Cycle Inventory Modelling of Land Use Induced by Crop Consumption. Part II: Example of wheat consumption in Brazil, China, Denmark, and the USA (to be submitted to *Int J LCA*).
24. Woltjer G, Banse M, Van Meijl H & Tabeau A, Alternative Approaches to Extend GTAP to Biofuel Crops, University, Indiana, USA, June 79, 2007, LEI (Agricultural Economics Research Institute), Paper submitted for the 10 th Annual GTAP Conference, Purdue. https://www.gtap.agecon.purdue.edu/resources/download/3258.pdf.
25. Netherlands Environmental Assessment Agency, Integrated Model to Assess the Global Environment (IMAGE), http://www.mnp.nl/en/themasites/image/index.html
26. Environmental Sciences Group, Wageningen University, The Conversion of Land Use and its Effects (CLUE) model http://www.cluemodel.nl/index.htm
27. Hellmann F & Verburg P H, Spatially explicit modelling of biofuel crops in Europe, Working paper, Land Dynamics Group, Department of Environmental Science, Wageningen University (2008).
28. Feng H, Rubin O D & Babcock B A, Greenhouse Gas Impacts of Ethanol from Iowa Corn: Life Cycle Analysis versus System-wide Accounting, Working Paper 08-WP 461, Center for Agricultural and Rural Development, Iowa State University, February, (2008).
29. Keeney R & Hertel T W, The Indirect Land Use Impacts of U.S. Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses, Department of Agricultural Economics, Purdue University, *GTAP Working Paper* No. 52 (2008).
30. Department of Transport, United Kingdom, The RFA carbon calculator version 1.0, Available at : http://www.dft.gov.uk/rfa/carboncalculator.cfm
31. E4Tech, Carbon reporting within the Renewable Transportation Fuel Obligation- Methodology, Final report, February (2008).
32. Lee H L, Hertel T, Sohngen B & Ramankutty N, Towards An Integrated Land-use Data Base for Assessing the Potential for Greenhouse Gas Mitigation, *GTAP Technical Paper* No.25, December, (2005).

33. MDIC-STI/IEL (Ministério do Desenvolvimento, Indústria e Comércio Exterior- Instituto Euvaldo Lodi – Núcleo Central), O futuro da indústria: biodiesel: coletânea de artigos. (eds.) José Rincon Ferreira, Carlos Manuel Pedroso Neves Cristo, Brasília (2006).
34. Conab, Consolidado e Acompanhamento da Safra 2006/2007, 1º Levantamento (2007). Available at: (www.conab.gov.br)
35. ABIOVE, Trigueirinho F, Biofuels Round Table: Production and Sustainability, Brazilian Association of Vegetable Oil Industries, Presentation at the *Brazilian – European Union Dialogues - Biofuels Round Table* - April 16, 2008.
36. ABIOVE (Brazilian Association of Vegetable Oil Industries), *Responsible production in soy agribusiness*, ABIOVE Report, April 2007.
37. Sheehan J, Camobreco V, Duffield J, Graboski M & Shapouri H, *An Overview of Biodiesel and Petroleum Diesel Life Cycles*, National Renewable Energy Laboratory, Report NREL/TP-580-24772, May 1998
38. Jungbluth N, et al. *Life Cycle Inventories of Bioenergy*. Swiss Center for Life Cycle Inventories, ecoinvent report No. 17, data v2.0 (2007).
39. Huntington G, *Animal Nutrition and Alternative Feedstocks*, Department of Animal Science, NC State University, presentation available at: http://www.cals.ncsu.edu/value-added/.
40. CONCAWE. *Well-to-wheels analysis of future automotive fuels and powertrains in the European context, Well-to-wheels report, version 2c*, Joint study by CONCAWE, EUCAR and the Joint Research Centre of the European Commission (2006).

Table 1. Data inputs for the optimization model.

	Value	Units	Reference
Biodiesel demand			
Domestic (2008) 2%	8.50E+08	l	MDIC-STI/IEL, 2006 [33]
Domestic (2020) 20%	1.24E+10	l	MDIC-STI/IEL, 2006 [33]
Exports (2008)	0	%	LASEN assumption
Exports (2020)	30	%	LASEN assumption
Soybean based-biodiesel (2020)	100	%	LASEN assumption
Soybean production and trade			
Soybean area A (2008)	2.20E+07	ha	Conab, 2007 [34]
Soybean area A (2020)	3.00E+07	ha	ABIOVE, 2008 [35]
Soy in rotation with Corn A (2020)	50	%	LASEN assumption
Soybean production A (2008)	5.89E+07	t/yr	ABIOVE, 2008 [35]
Soybean production A (2020)	1.05E+08	t/yr	ABIOVE, 2008 [35]
Soybean exports A (2008)	2.66E+07	t/yr	ABIOVE, 2007 [36]
Soybean exports A (2020)	4.74E+07	t/yr	LASEN assumption
Soy oil exports A (2008)	2.10E+06	t/yr	ABIOVE, 2007 [36]
Soy oil exports A (2020)	3.02E+06	t/yr	LASEN assumption
Yields			
Soy yield A (2008)	2.54	t/ha	Sheehan, 1998 [37]
Soy yield A (2020)	3.5	t/ha	ABIOVE, 2008 [35]
Soy yield A (intersowing) (2008)	2	t/ha	LASEN assumption
Soy yield C (2008)	2.54	t/ha	Sheehan, 1998 [37]
Soy yield B (2008)	2.6	t/ha	Sheehan, 1998 [37]
Corn yield B (2008)	8.95	t/ha	Argonne NL, 2006 [20]
Corn yield A (2008)	3.5	t/ha	Conab, 2007 [34]
Soy meal yield A (2008)	0.794	t_{meal}/ t_{soy}	Jungbluth, 2007 [38]
Oil extraction yield A-C (2008)	0.17	t_{oil}/ t_{soy}	Sheehan, 1998 [37]
Transesterification yield A-C (2008)	0.95	t_{bio}/ t_{oil}	Sheehan, 1998 [37]
Conversions			
Soy meal protein content A	47.5	%	Huntington, 2007 [39]
Corn protein content B	8	%	Huntington, 2008 [39]
LHV biodiesel A-C	37.2	MJ/kg	CONCAWE 2006 [40]
Biodiesel conversion allocation factor A-C	90%	%	CONCAWE 2006 [40]
Biodiesel density A-C	8.4 E+04	t/l	CONCAWE 2006 [40]
Emissions from land-use change			
Forest A	37	t_{CO2eq}/ha.yr	IPCC, 2006 [9]
Grasslands (inc. pastureland) A	10	t_{CO2eq} /ha.yr	IPCC, 2006 [9]
Cropland (incl. fallowland) A	0	t_{CO2eq} /ha.yr	E4tech calculation [30]
Forest B	17	t_{CO2eq} /ha.yr	IPCC, 2006 [9]
Grasslands (inc. pastureland) B	2	t_{CO2eq} /ha.yr	IPCC, 2006 [9]
Cropland (incl. fallowland) B	0	t_{CO2eq} /ha.yr	E4tech calculation [30]
Forest C	17	t_{CO2eq} /ha.yr	IPCC, 2006 [9]
Grasslands (inc. pastureland) C	2	t_{CO2eq} /ha.yr	IPCC, 2006 [9]
Cropland (incl. fallowland) C	0	t_{CO2eq} /ha.yr	E4tech calculation [30]
Carbon Payback Time (CPBT)			
Land-use change amortization	20	yr	IPCC, 2006 [9]
Emissions amortization / Projected years (2020-2008)	12	yr	LASEN assumption
CPBT Yield increment	0	t_{CO2eq}	LASEN assumption
CPBT Intersowing	0	t_{CO2eq}	LASEN assumption
Carbon intensity diesel (fossil)	8.64E-02	t_{CO2eq} /MJ	CONCAWE 2006 [40]
Carbon intensity biodiesel (soy) A	7.76E-02	t_{CO2eq} /MJ	CONCAWE 2006 [40]
Carbon intensity biodiesel (soy) C	4.76E-02	t_{CO2eq} /MJ	CONCAWE 2006 [40]

Table 2. LASEN's assumptions on certain strategic variables

Fixed variables ($\delta_{o,f,i,s}$, $\varepsilon_{o,f,i,s,k}$)	**Value**	**Units**
Intensification of soybean production for biodiesel in C	30	%
Intensification for soybean production in B due to shifting soybeans exports in A	30	%
Intensification for soy production for oil in C due to shifting soy oil exports in A	20	%
Intensification for corn production in B due to decease corn rotation in A	30	%
Intensification of pasture production in A due to pastures displacement by soy in A	35	%
Intensification of crops production in A due to crops displacement by soy in A (dir)	20	%
Avoided intensification of corn production for animal feed in B due to increase soy meal production in A	30	%
Soy expansion into forestland in C for soy-based biodiesel import to A	10	%
Cropland expansion into forestland in A due to crops displacement by soy in A	5	%
Soy expansion into forestland in B due to shifting soybeans exports in A	0	%
Pasture expansion into cropland in A due to pasture displacement by soy in A	0	%
Avoided corn expansion into forest for animal feed in B due to increase soy meal production in A	0	%
Soy expansion into forestland for oil production in C due to shifting soy oil exports in A	10	%
Corn expansion into forestland in B due to decrease soy-corn rotation in A	0	%

Table 3. Model outputs.

Var	Name	Original Value	Maximum (M)	Min	Max	20 yr
	Objective function					
-	Carbon payback time [yr]	331		-46	979	20
	Decision Variables					
i	Biodiesel imports from C	5%	30%	30%	30%	9%
i	Soybean exports shifted to biodiesel production in A	40%	50%	50%	50%	42%
i	Soy oil exports shifted to biodiesel production in A	30%	50%	0%	50%	27%
i	Corn area shifted from rotation to soybean production in A	30%	50%	39%	0%	34%
i	Soybean production by yield increment in A	30%	30%	0%	0%	30%
i	Soy area produced in intersowing in A	30%	50%	48%	6%	37%
i	Soy expansion into cropland in A due to increase demand for soy for biodiesel (dir)	16%	50%	0%	0%	0%
i	Soy expansion into grassland+pasture in A due to increase demand for soy for biodiesel (dir)	8%	50%	0%	10%	0%
i	Soy expansion into forest in A due to increase demand for soy for biodiesel (dir)	3%	50%	0%	50%	0%
s	Extensification for soybean production in B due to shifting soybeans exports in A	40%	50%	0%	50%	35%
s	Extensification for soy production for oil in C due to shifting soy oil exports in A	40%	60%	0%	60%	36%
s	Extensification for corn production in B due to decease corn rotation in A	40%	50%	0%	50%	33%
s	Extensification of pasture production in A due to pastures displacement by soy in A	50%	50%	0%	50%	0%
s	Extensification of crops production in A due to crops displacement by soy in A	60%	60%	0%	60%	0%
s	Extensification of soy production for biodiesel in C	40%	40%	0%	40%	28%
s	Avoided extensification of corn production for animal feed in B due to increase soy meal production in A	40%	50%	50%	0%	46%
k	Soy expansion into cropland in B due to shifting soybeans exports in A	70%	60%	60%	0%	60%
k	Avoided corn expansion into cropland for animal feed in B due to increase soy meal production in A	70%	70%	0%	70%	63%
k	Soy expansion into cropland for oil production in C due to shifting soy oil exports in A	50%	50%	0%	0%	50%
k	Corn expansion into cropland in B due to decrease soy-corn rotation in A	70%	60%	60%	0%	60%
k	Pasture expansion into grassland in A due to pasture displacement by soy in A	70%	70%	0%	0%	0%
k	Cropland expansion into crop+fallow land in A due to crops displacement by soy in A	30%	50%	0%	27%	0%
k	Soy expansion into cropland + fallow land in C for soy-based biodiesel import to A	60%	60%	60%	0%	60%
	Constraints					
-	Production constraint: Soybean production for biodiesel in BR equals soybean demand		$Soy_D=Soy_P$	7.94.E+07	7.94.E+07	7.94.E+07
-	Expansion constraint: Extensification of soy production for biodiesel in BR		$cae_{bio}<cae_{soy}$	0.00E+00	8.00E+06	0.00E+00

Table 4. Soybean production strategies and associated GHG emissions from LUC.

Soybean production strategy	**MIN**			**MAX**			**20 YEARS**		
	Soybean		**CO_{2eq}**	**Soybean**		**CO_{2eq}**	**Soybean**		**CO_{2eq}**
	Mt	**%**	**Mt**	**Mt**	**%**	**Mt**	**Mt**	**%**	**Mt**
Soybeans production from soybean export shifting	24	30%	-150	24	30%	109	20	25%	-18
Soybean production from oil export shifting	0	0%	0	9	11%	88	5	6%	20
Soy production by rotation shifting	11	14%	0	0	0%	150	10	12%	33
Soybean production by yield increment	0	0%	0	0	0%	0	22	27%	0
Soy production by intersowing	21	26%	0	3	3%	0	16	21%	0
Soybean production by crop area expansion	0	0%	0	20	26%	2767	0	0%	0
Soybean requirement for biodiesel imports	24	30%	0	24	30%	158	7	9%	21
TOTAL	**79**	**100%**	**-150**	**79**	**100%**	**3272**	**79**	**100%**	**57**

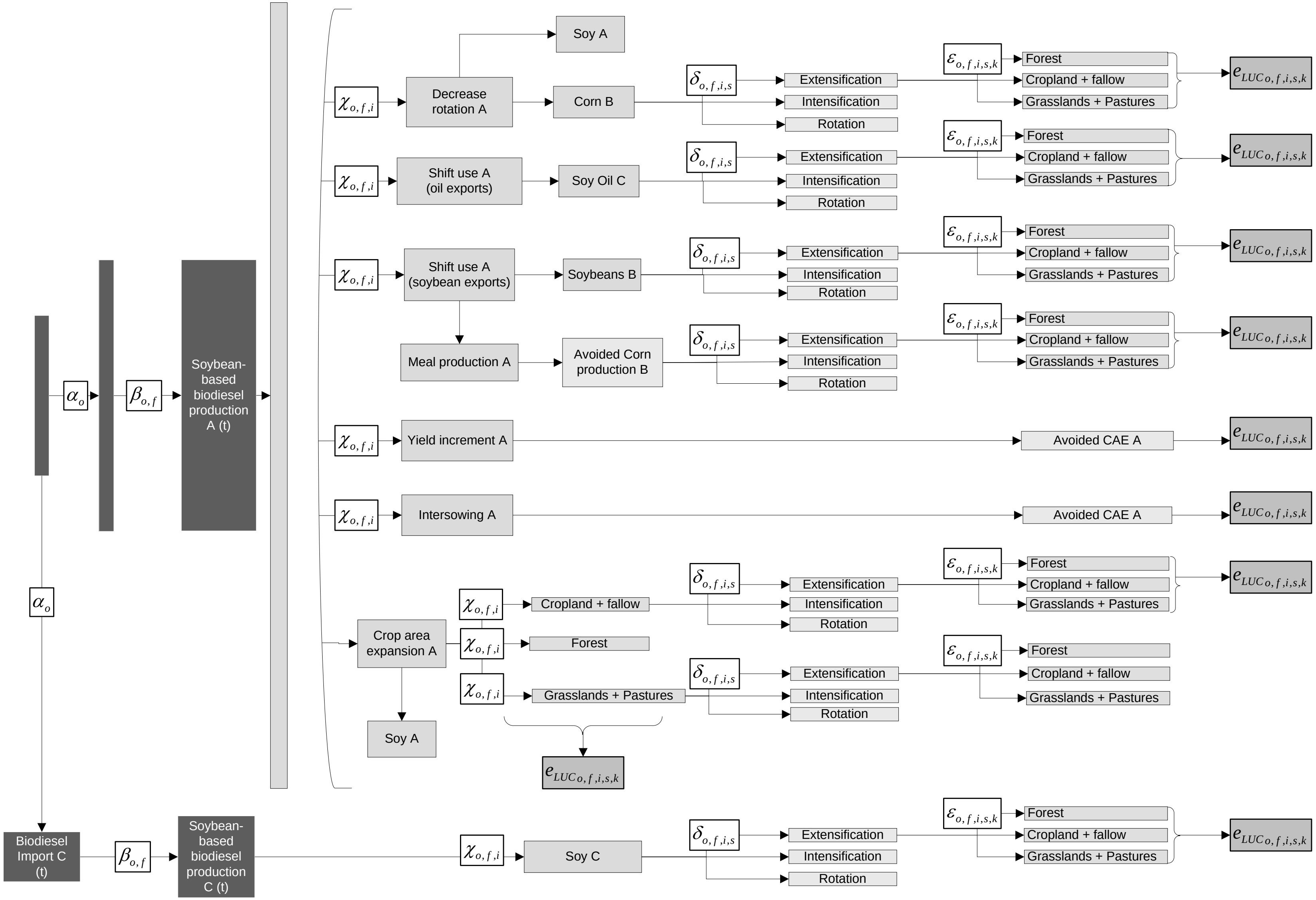

Figure 1. Soybean-based biodiesel production strategy.

Modified version published in: Journal of Scientific & Industrial Research, Vol. 67, November 2008, pp. 1017-1030