Biofuels, food security and regional development: a multiple objective model for cropland allocation outlined to assess microalgae's potential contribution to the Northeast Region of Brazil

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ABSTRACT

This paper presents a cropland allocation model intended to help decision makers to forge ex-ante balanced assessment of the impacts on regional development associated with the introduction of biofuels promotion policies. Considering a ten year time frame the model is applied to project the impacts of four biodiesel introduction scenarios in the Northeast Region of Brazil (NER). These include two B5 scenarios associated with the exclusive use of traditional oil crops and one B5 and one B10 scenario related to the introduction of microalgae-based biodiesel mixed with traditional oil crops. Four conflicting objectives, namely the maximization of the region's staple food autonomy; fuel autonomy; agricultural and fuel feedstock trade balance; and the number of job positions at the farm level drive the model. The multiple objective linear programming technique (MOLP) is used to pursue the minimal deviation from an ideal solution to the four objectives.

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Compromise programming (CP) is the tool adopted to find this point. Optimized CP scenarios increased annual cropland allocation to 14.58 million ha in the NER, year 2017, raising this amount by 32% and 16%, as compared to 11.04 and 12.81 million ha in current (2007) and baseline (2017) scenarios, respectively. As compared to the baseline scenario, cropland increases and the shift of commodities export dedicated cropland to the biofuel production sector in CP scenarios significantly increased the NER fuel autonomy (95%) and reduced the R$ 5,126 million reais deficit baseline agriculture and fuel feedstock trade balance by 79%. In the model, microalgae-based biodiesel economic contribution to the NER was negatively impacted by its high opportunity cost. When compared to traditional oil crops scenarios, microalgae-based biodiesel introduction scenarios could not significantly improve regional staple food autonomy, increasing this objective by 1% only. The NER fuel autonomy is positively impacted in the microalgae scenarios, but the increment as compared to the traditional oil crops scenarios is rather small, namely 2% and 7% in the B5 and B10 levels, respectively. These results indicate that the potential advantages expected for the microalgae-based biodiesel introduction did not materialize for the NER. It is concluded that the adoption of microalgae-based biodiesel is not an interesting biofuel alternative for the NER of Brazil under the current+10 years time frame adopted in this study. Contrary to the concerns usually referred to biofuel development, our model indicates that in the NER case, it is the commodity export, rather than the staple food agriculture feedstock production sector, that is mostly affected by the biofuel cropland allocation demand.

1 INTRODUCTION

It is an indisputable reality that energy consumption and development go hand in hand. Policymakers the world over are gravitating towards renewable bioenergy options to deal with the rising cost of fossil fuels, to address environmental concerns, provide new employment, and generate income opportunities for the rural poor (Dar, 2008).

In practice, however, sustainable biofuel production and/or its introduction in an existing energy matrix is subject to all kinds of controversies, many of them related to cropland use and allocation. For instance, in Africa, staple food cropland managed under low intensity systems is now being bought by large international companies and being shifted to biofuel feedstock production. In South East Asia, in its turn, African palm farmers are considered to be responsible for mass deforestation of pristine ecosystems, despite the existence of large degraded forest land suitable to biofuel feedstock production. In a similar way, sugarcane plantations have been linked to the occupation of previous dedicated pasture lands in Central Brazil which, in turn, are now pushing further deforestation into the Amazon Region (Ernsting, 2007).

In this context, the use of microalgae as a feedstock for biodiesel production is being researched as a potential alternative to reduce the pressure on the food production croplands. Among others, microalgae potential advantages refer to the high efficiency at which these small organisms deal with the sunlight energy (Benemann and Oswald, 1996). In fact, expected individual photosynthesis and biomass accumulation are about 5 times faster in microalgae when compared to higher order plants (van Harmelen and Oonk, 2006). Moreover, to maintain these significant growth rates, the microalgae demand elevated quantities of CO_2. By producing biofuels and at the same time consuming CO_2, microalgae production offers the possibility of a win-win scheme, addressing two of the key current environmental issues. The main challenges to the large scale adoption of this alternative, however, are the high production costs, the difficulty of maintaining high productive pure cultures of the desired microalgae species in open ponds, and the presumably low energy efficiency when using microalgae production based on closed systems (photo bioreactors; Rodolfi et al., 2009). Referring to the microalgae-based biodiesel production, Pate (2008) considers the issues involved in efficiently introduction of this new biofuel in an existing energy matrix as a very complex and dynamically interdependent “metasystem” problem.

One form to efficiently face these issues is to reduce the scale of one’s study target area. In fact, the planning and policy development for alternative biofuels introduction is relevant and must be pursued not only at the national level, but also on a regional basis. The regional scale may permit a better assessment of the resources available and a more realistic understanding of the environmental and socio-economic issues involved in the use of these resources for any defined objective.

Policymakers, nevertheless, are confronted with a large number of goals and objectives as desired outcomes of the new policies, and biofuels introduction is no exception. Such goals may include balancing income distribution through the adoption of biofuel crops in family scale farms, maximizing the reduction of imported petroleum, minimizing regional CO_2 emissions from burning fossil fuels, reducing land use competition with the food production as well as integrating local small and medium scale biofuel industries.

In order to develop these goals the planner has to make decisions regarding the level of activities that would strike an acceptable balance among such often conflicting goals (El-

Gayar and Leung, 2001). Moreover, the planner is constrained by the resources available in the region such as land, labor, fertilizer, etc., as well as other external constraints such as domestic market staple food and fuel demand, export market demand, and pollution control restraints. A multiple criteria decision making (MCDM) model seeks to efficiently assist the planner in identifying feasible alternative decisions that suit existing resources and external constraints.

In order to obtain a balanced maximization of the regional net benefits of staple food, export commodities and biofuel conflicting demands, a MCDM model was developed and applied to the Northeast Region (NER) of Brazil as an example. The microalgae impact as one of the biodiesel feedstock alternatives is assessed since it is considered an alternative that saves cropland. The study specifically pursuits to offer for decision makers insights to the following questions: what is the biodiesel feedstock production impact on the regional staple food production, on the regional fuel autonomy and on the creation of job positions at the farm level related to biofuel feedstock production? What is the regional economic balance related to agricultural and fuel feedstock production? And finally, what would be the role of microalgae-based biodiesel introduction as compared to traditional biodiesel crops feedstock production in the Northeast Region (NER) of Brazil.

2 MATERIAL AND METHODS

The main methodological components detailed in this section encompass the multiple objective mathematical programming model, the application of the compromise programming technique and finally the scenarios analysis characterization.

2.1 *The MCDM model and theoretical framework*

The MCDM model herein is based on the quantification of annual and perennial cropland allocation between twelve crops cultivated among the three main farm types present in the Northeast Region (NER)[1]. The feedstock production originated from these crops is then allocated among three main feedstock demanding sectors, namely, staple food, commodity export, and biofuel production (Figure 1). Next, the detailed description of the model is presented.

2.1.1 Model decision variables

Considering the relations among available cropland, farm types and cropland dedicated to each of the feedstock sectors as presented in Figure 1, the decision variables herein are defined as the cropland areas allocated for each of the twelve crops presented in Table 1, produced by each of three farm types (agribusiness, family scale and subsistence) and dedicated to each of the three feedstock demanding sectors, namely, staple food, export commodities and biofuels.

Mathematically, the decision variables in the model are represented by:

$$x_{igt} \tag{1}$$

where, the decision variable x_{igt} is the planted area for crop *i* dedicated to the feedstock sector *g* and produced in farm type *t*.

[1] For a review and characterization of the NER's agricultural sector, refer to Boll (2011).

2.1.2 Model objectives

Regarding cropland use, biofuel development clearly conflicts with other agricultural feedstock industries, especially the food and the export commodities sectors. In order to achieve a balanced set of objectives for the model, the model objectives selection was based on literature review on sustainable indicators and goals to be pursued in biofuels development and also in sustainable development of the NER (UN, 2007).

Some preliminary runs of the model indicated that economic objectives are the ones that best fit these criteria. Therefore, one of our objectives in the present model refers to the aggregated economic contribution of the different agricultural feedstock production sectors and the fuel balance to the regional economy. Departing from the macroeconomic identity, it is possible to quantify the amount of external resources received by one region and also those generated through inter-regional and international trade (Haddad et al., 2002).

$$Y \equiv C + I + G + (X - M)_{reg} + (X - M)_{\mathrm{int}} \tag{2}$$

where, Y = gross regional income; C = regional consumption expenditure; I = gross investment in the region; G = government expenses balance in the region; $(X - M)_{reg}$ = regional trade balance with other regions in the country; and $(X – M)_{int}$ = international trade balance with other countries.

The model uses a simplified version of this equation in order to track the partial regional economic balances related to the supply and demand balance of each of the agricultural feedstock sectors and fuel sector. In this the case equation (2) was simplified to:

$$Max\ Y_{g\ par} = \sum_{i=1}^{n} \left(G_{ig} + (X - M)_{ig} \right) \tag{3}$$

where, $Y_{g\ \mathrm{par}}$ = partial regional economic balance related to agricultural feedstock production sector *g* (Brazilian currency reais; R$); G_{ig} = federal government transfers balance related to feedstock production *i* dedicated to sector *g* (R$); and $(X – M)_{ig}$ = inter-regional and international equivalent trade balance for feedstock *i* dedicated to production sector *g*. The specific partial economic balances are calculated in a similar fashion for each of the three agricultural feedstock sectors as detailed by Boll (2011).

Regional autonomy for staple food feedstock is a critical indicator that may be affected by an aggressive biofuel development policy. Based upon an average regional staple diet (see Table 2), the equivalent staple food feedstock demands have been estimated based on the NER population growth estimates (IBGE, 2006). Once these variables are quantified, the regional autonomy for staple foods is calculated as a percentage of the equivalent regional staple food feedstock demand. Therefore, the second objective of the model herein is represented as:

$$Max\ \ Stf_{aut} = \sum_{i=1}^{11} \frac{Stf_i}{StfDe_i} \tag{4}$$

where, Stf_{aut} = staple food equivalent feedstock autonomy (%); Stf_i = crop *i* staple food production (t); and $StfDe_i$= crop *i* staple food demand (t).

The third objective in the model is the regional fuel autonomy. The regional fuel autonomy is an important indicator to evaluate the success of biofuels introduction policies. In the same token as adopted for the staple food autonomy, this objective is calculated herein as follows:

$$Max\ \ Fuel_{aut} = \sum_{w=1}^{2} \left(\frac{Ff_{w'} + Biof_{w}}{FuelDe_{w'}} \right) \qquad (5)$$

where, $Fuel_{aut}$ = regional fuel autonomy (%); $Ff_{w'}$ = regional fossil fuel *w'* production (boe); $Biof_{w}$ = regional biofuel *w* production (boe); and $FuelDe_{w'}$= regional fuel *w'* demand (boe).

The fourth and last objective in the model estimates the number of on farm jobs related to the three agriculture feedstock production sectors, relating dedicated crop areas to each of these sectors and to the job opening parameters. Based on the Brazilian 1995/96 agriculture census information, the INCRA/FAO (2000) report concluded that in the NER, on average, one worker is needed for each 5 ha on family scale farms (including subsistence farms), while for the agribusiness farm type in the same region on average one person is required for every 42 hectares of land. Specifically for sugarcane production, the number of 23 ha per job position is used for both the family and the agribusiness farm types. Mathematically, these relations are expressed as:

$$Max\ \ J_{g} = \sum_{t=1}^{3} \sum_{i=1}^{n} j_{t} \,.\, x_{igt} \quad \text{for } g = 1, 3 \qquad (6)$$

where, J_g = farm level job positions for agriculture feedstock sector g; j = number of job positions linked to farm type t; and x_{igt} = crop area for crop i produced by farm type t and dedicated to feedstock sector g.

2.1.3 Model constraints variables

Besides decision variables and objectives, the third element in optimization model is the constraint. In the present model these constraints consist mostly of crop area related constraints. For instance, the summation of the crop areas dedicated to annual crops cannot exceed the available annual crop area in the target region, according to the following equation:

$$\sum_{i=1}^{9}\sum_{g=1}^{3}\sum_{t=1}^{3} x_{igt} \leq An_{\max} \qquad (7)$$

where x_{igt} = annual crop i area dedicated to sector g feedstock production in farm type t (ha); and An_{max} = maximum annual cropland available in the target region. By the same token, the perennial cropland dedicated to the three feedstock sectors in this model cannot exceed the maximum perennial cropland available in the region, as follows:

$$\sum_{i=1}^{3}\sum_{g=1}^{3}\sum_{t=1}^{3} x_{igt} \leq Pe_{\max} \qquad (8)$$

where, x_{igt} = perennial crop *i* area dedicated to sector *g* feedstock production in farm type *t* (ha); and Pe_{max} = maximum perennial cropland available in the NER.

Since available cropland is also divided among three different farm types, this study includes a constraint in which the maximum annual crop area for each farm type is defined, considering the crop shares presented in Table 4, and the following equation:

$$\sum_{i=1}^{9}\sum_{g=1}^{3} x_{igt} \leq An_{t\ \max} \qquad \text{for } t = 1, 3 \tag{9}$$

where, x_{igt} = annual crop *i* area cultivated in farm type *t* and dedicated to sector *g* (ha); $An_{t\ max}$ = maximal annual cropland share available for farm type *t* in the NER region.

The same type of constraint is applied for the perennial cropland in a similar way:

$$\sum_{i=1}^{3}\sum_{g=1}^{3} x_{igt} \leq Pe_{t\ \max} \qquad \text{for } t = 1, 3 \tag{10}$$

Moreover, each crop is constrained to a specific maximum crop area value (X_i). The methodology used to calculate this maximum area is referred to in sub-section 2.3.2 below.

$$\sum_{g=1}^{3}\sum_{t=1}^{3} x_{igt} \leq X_{i\ \max} \qquad \text{for } i = 1, 9 \tag{11}$$

Additional constraints in the model do not relate to cropland issues per se. The first of them limits the staple food feedstock production in the region, up to the equivalent amount of feedstock that supplies the total regional staple food demand.

One additional constraint is related to biofuel policies, defining the minimum volume a certain biofuel must occupy in the regional fuel consumption. These biofuel supply levels refer to the use of microalgae-based biodiesel, which is constrained to supply at least 50% of the regional biodiesel demand in selected scenarios (more on this in sub-section 2.3 below). All the assumptions related to the microalgae production considered herein were detailed by Boll (2011).

The third additional constraint in the model refers to the screening of oil crops to be used as biodiesel feedstock according to their production costs. Basically, this constraint excludes from the biodiesel alternative those oil crops whose farm gate price is not compatible to current NER biodiesel production costs. This constraint is referred to as the biodiesel market attractiveness to crop *i* (AtBio). This constraint must be positive in selected scenarios, which is expressed through the following equation.

$$AtBio_i \geq 0 \tag{12}$$

The biodiesel market attractiveness for crop *i* is composed of two components, namely the processing threshold price and the feedstock threshold price. These components are calculated through a sequence of calculations presented in Boll (2011). The final step in these calculations is presented below.

$$AtBio_i = \left[\frac{\left(P_i - TP_{fedk}\right)}{P_i} \right].100 \tag{13}$$

where, AtBio = biodiesel market attractiveness for crop *i*; P_i = current farm gate price for crop *i* feedstock; TP_{fedk} = threshold price for crop *i* feedstock.

The fifth and final constraint states that all the decision variables must be positive:

$$x_{igt} \geq 0 \tag{14}$$

2.2 *The compromise programming technique (CP)*

In multiple criteria decision making terminology, attributes are defined as a set of decision maker's values related to an objective reality (El-Gayar and Leung, 2001). Such values, as presented in the previous section, can be measured independently from decision maker's desires and in many cases are expressed as a mathematical function of the decision variables.

In situations where definite goals for the achievement of multiple objectives are not known in sufficient detail for them to be expressed as targets, the multiple objective programming (MOP) has proved a useful tool (Romero and Rehman, 2003).

The main purpose of MOP, or vector optimization techniques, is to help to solve the problem of simultaneous optimization of several objectives subject to a set of constraints, which are usually linear. It seeks to identify the set that contains efficient (non-dominated or Pareto optimal) solutions since an optimal solution for several simultaneous conflicting objectives is not defined (Romero and Rehman, 2003). The elements of the efficient set are the feasible solutions with the property that there are no other feasible solution that can achieve the same or better performance for all the objectives, and strictly better for at least one objective. Linear programming is an adequate technique to find each of these solutions individually, turning MOP to MOLP (Ragsdale, 2004).

The CP technique assumes that any planner seeks a solution as close as possible to the ideal point, with the smallest deviation from the relevant objectives. To determine that optimum solution somehow it is necessary to introduce the decision maker's (DM) preferences. CP does that in a very realistic way, without having to rely on the questionable assumptions of the utility theory (Romero and Rehman, 2003). As a first step, an ideal (utopian) solution is identified. This solution works as a point of reference for the DM. Thereafter, CP assumes, quite realistically, that any DM seeks a solution as close as possible to the ideal point, possibly the only assumption made by CP to human preferences.

When CP is used under a continuous setting, the best-compromise (ideal) solution is obtained straightforwardly from conventional linear programming (LP) models. The general formulation of a CP approach is expressed as follows (Romero and Rehman, 2003):

$$Min\left\{ L_p = \left[\sum_{j=1}^{n} W_j^p \left| \frac{\left(Z_j^* - Z_j(\underline{x})\right)}{Z_j^* - Z_{*j}} \right|^p \right]^{1/p} \right\} \tag{15}$$

subject to

$$\underline{x} \in \underline{F} \tag{16}$$

where, L_p is the distance metric, for any p in which $0 < p < \infty$; W represents the importance of the discrepancy between the jth objective and the ideal point, n is number of objectives and $\underline{F}$ is the feasible set (limited by the model constraints). The weights assigned for the objective functions (W) in the present model all have the same value and are equal to 1.

In equation (15), p is the metric parameter. Different values of p represent different aspects of a compromise programming algorithm. For $p = 1$, all deviations from Z_j^* are directly proportional to their magnitude. In other words, to minimize L_1 is to minimize the sum of the deviations verified in each objective in relation to its optimal value. Considering that there is a family of L_p distances, it is also possible to calculate the L_∞ distance, known as the Chebyshev distance. This time the maximal distance among the objectives in the model from their respective ideal points is minimized, instead of their sum, as presented for L_1. As put by Poff et al (2010), varying p from 1 to ∞, allows to move from having a perfect compensation among the objectives (i.e., minimizing the sum of individual deviations) to having no compensation among the objectives in the decision making process (i.e., minimizing the maximum deviation).

The MINIMAX objective function can efficiently be used in these conditions to obtain the minimization of the maximal deviation (L_∞) between the objectives considered in the problem and the ideal solution (Ragsdale, 2004). An additional advantage of the MINIMAX technique is that it allows the exploration of non-corner solutions, expanding the options available to the DM. Herein, only the MINIMAX distance is considered.

Modern spreadsheet environments, such as the one in Microsoft's Excel™, offer adequate conditions to implement and solve this type of MOLP, including those involving compromise programming as proposed in this study. Herein this was accomplished through the use of Premium Solver™, an enhanced Excel add-in from Frontline Systems.

2.3 *The biodiesel development scenarios*

The comparisons among the potential effects on biodiesel adoption in this study are performed through the use of scenario analysis (Grossman and Özulük, 2009), aiming to offer the DM with relevant information on biofuel development issues. Rather than a complete picture for the whole regional economy, agriculture sector and land use figures, the focus herein is on the changes introduced by different biodiesel alternatives and adoption levels, comparing them to a baseline scenario. Riedacker (2007), considering the dynamics of land use and the constant changes in the world basic needs, recommends that new policies for the agricultural sector development should be evaluated in the scenarios level, rather than in absolute numbers.

The model considers two time frames only, namely the current, or initial situation (Ini), which reflects the 2007 regional crop production, and secondly, the projected time frame, namely Initial+10 years (2017). In the projected Initial+10 years time frame situation there are five scenarios considered: one baseline scenario and four CP optimized scenarios. Each of these scenarios characterization is presented next and summarized in Table 5.

2.3.1 The initial scenario (INI)

The initial scenario represents the current situation in the NER and reflects year 2007 figures. Unless otherwise stated, all expressed values for the initial scenario (Ini) are obtained by averaging NER cropland allocation and feedstock production over three years (2005 to 2007). Regarding biofuel adoption in the NER, the initial scenario considers the presence of ethanol, but not biodiesel (Table 5).

2.3.2 The projected scenarios (INI + 10 years)

Projected scenarios represent NER estimated situation in current +10 years time frame. Projections for agricultural production increments in the model follow an adaptation from the original methodology used for feedstock production estimation presented by the Oak Ridge National Institute – ORNI (Kline et al., 2008). In this method, future crop production is a function of two variables: area expansion (crop area) and technology level (crop productivity). Based on empirical data collected over the past 10 years, the historical compound growth rates for crop area and crop productivity is estimated for each potential biodiesel feedstock producing crops (n=6), the main target of the model. Additional staple food and commodity crops growth rates are obtained as a proxy from these crops (averaged compound growth rates according to the culture type, e.g., annual and perennial).

There are two types of projected scenarios in the model:

a. Baseline scenario

The baseline scenario (Base) reflects the business as usual cropland and productivity expansions of the initial situation (Ini) projected to the Initial+10 years time frame. This scenario is the benchmark to which the multiple objective optimized scenarios will be compared. Biodiesel is absent from the regional fuel pool in initial situation (Ini) and therefore, also in the baseline (Base) scenario.

b. CP optimized scenarios

The second type of projected scenarios is the CP optimized scenario. There are four CP scenarios in the analysis and they are divided in two groups, namely traditional oil crops and traditional plus alternative crops (microalgae). In the first group, the use of traditional oil crops only is considered as potential biodiesel feedstock. This group includes two scenarios: the B5 scenario includes all oil crops available in the NER as potential biodiesel feedstock sources. The B5+ec scenario, in its turn, constrains the oil crop participation in biodiesel production to those crops that show a positive value for the market attractiveness constraint. In other words, in this scenario (B5+ec), only those crops that have competitive farm gate prices with regional biodiesel production costs are included in the feedstock mix to produce biodiesel (Table 5).

The second group of CP optimized scenarios considers the adoption of the microalgae alternative in the mix of biodiesel feedstock sources. This scenario group considers two scenarios where microalgae-based biodiesel is assumed to supply at least 50% of the NER demanded biodiesel, namely the B5 and the B10 biofuel levels. Brazilian policy set the year 2013 as the year when 5% of the diesel oil in the country will be mandatory replaced by biodiesel (Dornelles, 2006).

2.4 *Data sources*

All information assessed in this study regarding cropland use, crop productivity and farm gate crop value were obtained from IBGE (Brazilian Institute of Geography and Statistics) online data bank PAM (Municipal Agriculture Production; IBGE, 2009). Regarding the NER's international imports and exports information, the data was obtained from the online data bank ALICE, maintained by the Brazilian Ministry for Industry and Trade; AliceWeb, 2009). Although the NER showed international trade figures for coconut, corn and cotton over the last three researched years (2005 to 2007), they represented less than 1% of their respective equivalent feedstock production in the region and were not considered in this study. Soybeans, sugarcane and coffee, on the other hand, do show significant average export volumes during the same period, namely, 75, 32 and 31% of the equivalent feedstock produced in the NER between 2005-2007 ; (AliceWeb, 2009). Commercialization figures related to fuel and biofuels in the NER were obtained from the National Petroleum Agency website (ANP, 2009). Technical coefficients for the fuels and biofuels are presented by Davis et al., 2008).

3 RESULTS AND DISCUSSION

The results obtained in this study are presented next in next two sections. First, the NER 2007's initial situation (Ini) is compared with the 2017's baseline scenario (Base), which is the initial situation (2007) projected to the Initial+10 years time frame (2017). Next, the results obtained in the compromise programming optimized scenarios (2017) are presented and compared to the baseline scenario (Base).

3.1 Initial situation (Ini) and the projected baseline scenario (Base)

The NER cropland initial situation indicates the use of close to 11.04 and 0.44 million hectares (M ha) of cropland allocated among the nine annual and three perennial crops considered in this study, respectively (Tables 6 and 7).

As indicated in section 2.3.2 above, based on historic cropland expansion rates verified for the crops over the past ten years our model projects for year Ini+10 years (2017) an overall 16 and 19% increase in annual and perennial cropland allocation in the region, reaching 12.81 and 0.52 M hectares, respectively, (Tables 6 and 7). Excluding fallow land, three crops account for 89% of the annual cropland increment in the NER, namely sugarcane (44%), soybeans (24%) and cotton seeds (21%). Corn (4%) and beans (3%) present the next most significant participation in the cropland expansion, followed by cassava, rice, castor beans and peanuts, with participations ranging around 1% each (results not presented).

Regarding perennial crops, 46% of the cropland increment is projected to occur in coffee plantations, while coconut and African palm showed projected cropland expansions in the order of 33% and 21%, respectively (results not presented). It should be noted that the three perennial crops considered in the model occupy 10% of the perennial cropland available in the region.

Table 8 presents the summary of the results related to the four objectives considered in the model as calculated for the NER Initial (2007) and Baseline (2017) scenarios. Our projection indicates that biofuel production (ethanol only) would occupy 4% of the available annual cropland in the NER in the year 2017 Baseline scenario. This 37% increment in the biofuel dedicated cropland would be enough to produce 82% of the 2017's NER projected ethanol demand (Table 8; item I). The regional fuel economic balance, however, would fall 89%, from a deficit of R$ 3,115 in 2007 to R$ 5,890 million reais in year 2017 (Table 8; item II). The NER fuel autonomy would also fall 31%, from estimated fuel autonomy of 55% in 2007 to 38% of the 2017 regional projected fuel demand (Table 8; item III).

These projections indicate that the combined fossil fuel plus biofuel demand in the NER is growing in a faster pace than the regional fossil fuel and biofuel production. In fact, according to ANP (2009), NER extracted petroleum production has shown a negative average growth rate of -1.87% $year^{-1}$ between 2000 and 2006 (Figure 3).

The significant increase in the regional fuel deficit (31%), allied to the reduced increase in staple food production (4%; Table 8), end up significantly reducing the potential benefits that cropland expansion, agricultural productivity and especially the agricultural commodity export sector growth would bring to the NER in the year 2017. Therefore, the comprehensive economic feedstock balance for the region in 2017 is projected to increase an insignificant amount of 3% as compared to actual Initial situation, reducing the regional annual deficit of R$ 5,312 million Reais by R$ 185 million only (Table 8; III).

3.2 *CP optimized scenarios*

Considering the launching of the Brazilian biodiesel program and based on the baseline scenario results presented in the previous section, the main objective of this section is to search for optimized cropland allocation schemes that contribute to outline a more balanced horizon for the NER development, including regional independence on imported food and energy resources. The first step in this process is to individually maximize each of the four objectives of the model. The individual optimization results in the 2007+10 years time frame of each of the four objectives, as well as the baseline scenario results, are presented in Table 9. The doted box in the table shows the payoff matrix for these four objectives. The bold values indicate the maximal attainable results for each individual objective.

The results presented in Table 9 indicate that there is a potential in the NER cropland allocation for optimization in all the four objectives as compared to our baseline projection. There are, however, trade-offs between the model objectives which should be taken into account by the DM.

As detailed in the methodology section above, through the use of the compromise programming technique (CP) it is possible to find balanced solutions that minimize the normalized maximal distances among the objectives and their respective ideal values. This distance is referred to as the L_∞ distance, also known as the MINIMAX. Next, the results generated through the use of the CP technique in four different biodiesel implementation policy scenarios, namely traditional oil crops (B5); traditional oil crops economically constrained (B5+ec), traditional plus microalgae feedstock use (B5+m), and expanded traditional oil crops plus microalgae (B10+m) are presented and discussed.

Table 10 shows the NER annual cropland allocation results for the baseline and four CP optimized scenarios[2]. As expected, optimization pushed annual cropland use to 14.58 M ha in all CP scenarios, a 14% increase over the baseline figure, namely, 12.81 M ha. Moreover, when compared to current Initial (2007) cropland use in the region scenario, 11.04 M ha, CP results represent an increase of 32% in annual cropland allocation for year 2017 (percentages not shown).

Table 11 presents the estimated ethanol and biodiesel production figures in four CP scenarios as compared to the NER projected ethanol and biodiesel demands for the year 2017. African palm and castor beans are the two oil feedstock sources strongly supported by the Brazilian Biodiesel Program (Dornelles, 2006). Nevertheless, the exclusion of the castor beans as biodiesel feedstock in B5+ec scenario indicates that the current subsidies level offered to castor beans based biodiesel is not sufficient to make this feedstock economically competitive in the NER of Brazil. These results are in line with the biodiesel attractiveness results obtained for the main NER oil crops presented by Boll (2011). African palm, on the other hand, has a positive market attractiveness index and therefore is included by the model in the CP optimized scenarios feedstock pool. The low productivities and slow crop expansion rates registered for this crop in the NER over the last ten years, however, limit its biodiesel supply to be no more than 1% of the projected 2017's NER biodiesel demand. Besides African palm, cotton seed and soybeans are the

[2] Due its relatively reduced area and less significant impacts, perennial cropland allocation results in CP scenarios are not presented

other two oil crops that present positive biodiesel market attractiveness indexes. The CP optimization model, however, allocated only soybeans as a biofuel feedstock. Our baseline scenario projects a large area producing soybeans in the NER in 2017 (1.81 million ha; result not shown) and the productivities achieved for this culture in the NER are already among the highest in Brazil. Therefore, the NER produces enough soybeans feedstock to supply the vegetable oil demanded as staple food, a significant portion of the regional biodiesel demand and still presents surplus amounts for available exportation. The model takes advantage of these figures to allocate soybeans as the main conventional oil feedstock for the NER.

When microalgae feedstock is introduced to the biofuel feedstock pool, significant surpluses of biodiesel are produced in the NER. The microalgae producing area demanded to achieve these production levels, however, is 200 and 399 thousand hectares of microalgae ponds managed under the characteristics described by Boll (2011) for the B5+m and B10+m scenarios, respectively. While the economic impacts of this alternative will be further discussed below, considering current research scale it seems highly improbable that such a large scale industry will be technically feasible and in operation over the next 20 years.

Table 12 presents the NER economic trade balances for the staple food, commodity export, biofuel and the fuel feedstock sectors in the baseline and four CP scenarios.

The changes in the four trade balances presented in Table 12 (staple food, commodities, biofuel, and fuel feedstock) are summarized in the model through the comprehensive feedstock economic objective. This objective shows very significant improvements in all CP scenarios (Table 13).

As compared to the baseline result, with a comprehensive trade deficit for the NER of R$ 5,126 million reais, the CP scenarios showed on average an 82% deficit reduction, to about R$ 941 million reais. This reduction derives from two main factors. First, there is a more balanced cropland allocation between the biofuel and export commodity production sectors in the CP scenarios. This significantly reduces the NER fuel sector economic deficit projected in the baseline scenarios. Secondly, as expected, cropland allocation in the CP scenarios is maximized, expanding NER crop areas allocation in all farm types, but more significantly in the agribusiness type of farms. As shown in Table 13, traditional oil crops scenarios showed the best comprehensive trade results, with an average comprehensive trade balance deficit of R$ 542 million reais. Microalgae scenarios had an average deficit of R$ 1,341 million reais, with the B10+m scenario showing the smallest, but still significant, trade deficit reduction, to R$ 1,605 million reais, a 73% reduction in comparison to the baseline deficit value of R$ 5,126 million reais.

The second objective in the model is to maximize the region staple food autonomy. The significant improvement in the NER regional staple food trade balance verified above (Table 12), however, contrasts with the small average increment (6%) in the regional staple food autonomy objective verified for the CP scenarios (Table 13). This fact is explained by the methodology adopted to calculate the regional staple food autonomy, which is based on the physical quantities of feedstock produced in comparison to their respective regional demand. Through this methodology, the shift of 77% of secondary staple food sugarcane cropland to the biofuel sector significantly impacted the regional staple food objective, counterbalancing the sum of the increments in four other core NER staple food crops, namely beans, cassava, corn and rice (Figure 4).

It is proposed that future studies use an alternative objective to track staple food autonomy, for instance, the regional autonomy on core staple food crops only, e.g., rice, beans, cassava, wheat, etc. Another alternative is to express the regional staple food autonomy as the locally produced fraction of the staple food feedstock economic value demanded by the target region.

In contrast to the staple food sector, commodity export contribution to the NER economy is significantly reduced in CP scenarios. As presented in Figure 5, there is a direct relation between the reduction in commodity export allocated cropland and the cropland allocated for two of the main biofuel crops in the NER: sugarcane and soybeans.

Out of the additional 2.138 million ha of sugarcane and soybeans allocated to the biofuel sector in the CP scenarios (average values), 92% were shifted from the export sector and only 0.181 million ha from the staple food sector (Figure 5). We attribute these figures to two correlated factors. First, staple food is the largest feedstock sector among the feedstock sectors included in this study. Therefore, the model looks for solutions that reduce the staple food deficit first. Secondly, staple crops production occurs mainly in the family scale farms.

As shown in Table 4, the share of the NER production of beans, cassava, corn and rice originated from family scale farms is 74%, 77%, 61% and 66% respectively. At the same time, as presented in Table 10, family scale farms available annual cropland in the NER is 100% allocated in the CP scenarios, leaving no room for additional cropland allocation to reduce the region staple food deficit. The next option in the model is to reduce the fuel importations expenses, the second largest deficit in the NER feedstock balance (Table 13). Consequently, the export sector is heavily impacted and ends up shifting about 63%

of its baseline cropland to the biofuel sector in the CP scenarios (Table 10). Sugarcane and soybeans account for 75% of this shift (Fig. 5).

Figure 6 shows the individual cropland allocation for the biodiesel feedstock crops in four CP scenarios. As already mentioned, the introduction of the economic constraint in the B5 scenario (B5+ec) implied in the exclusion of castor beans from the biodiesel feedstock pool. Surprisingly, the model does not allocate additional soybeans or other oil source cropland to the biofuel sector. In fact, soybeans cropland dedicated to biodiesel feedstock production in the B5+ec scenario is reduced by about 0.191 million ha as compared to the B5 scenario (Figure 6). These figures indicate the close linkage between commodity export and biofuel production in the NER. The necessity to increase the region's trade balance end up outlining only slight differences among cropland allocated to the export commodity sector to increase the region's income, or to the biofuel sector, to reduce the regional fuel importation expenses. Therefore, the difference in the comprehensive feedstock balance between the B5 and B5+ec scenarios is only 3%, or about R$ 15 million reais (Table 13).

As expected, the introduction of the microalgae alternative feedstock supplying at least 50% of the NER biodiesel demand ended up favoring a small shift of soybeans to the export sector (Figure 6). Moreover, the region fuel autonomy, the third objective in the model, showed positive increments of 2% and 7% in the microalgae scenarios B5+m and B10+m, respectively, as compared to the traditional oil feedstock scenarios (Table 13). Nevertheless, this increase in export dedicated feedstock and in the fuel autonomy objective was not enough to compensate the microalgae increased biofuel opportunity cost, resulting in a decreasing comprehensive trade balance for the target region.

Microalgae scenarios B5+m and B10+m showed comprehensive feedstock trade balances about 96% and 192% larger, respectively, than the average results verified for traditional oil crops scenarios (B5 and B5+ec; Table 13). Most importantly, as recorded in this optimization model, the introduction of microalgae production areas as significant as 200 and 399 thousand hectares, did not result in a significant increment in regional staple food production cropland availability, and consequently did not reduced significantly the NER staple food trade deficit, one of the most cited microalgae promotion arguments [4]. The fourth and last objective in the model refers to the maximization of job positions at the farm level in the NER. While, on average, the CP scenarios increased the number of job positions by 22% as compared to the baseline projection, there were only slight differences among the CP scenarios (Table 13). Through cropland allocation optimization in the CP scenarios, the model allocates the maximal cropland available in each farm type, as well as in each feedstock sector. Therefore, final values for cropland allocation in each of the farm types have the same value in the four CP optimized scenarios (see Table 10 above). Since farm level job positions in the model depend on cropland allocation, there are little differences among the scenarios. In fact, the largest difference among the CP scenarios was 1% and occurred between the B10+m and the traditional oil crops scenarios B5.

According to the Brazilian biodiesel law, at least 50% of the oil crops feedstock allocated for biodiesel production in the country should be originated from family scale farms. Results presented in Figure 7 indicate that biodiesel feedstock production in our CP scenarios occurred predominately through the agribusiness type of farms (>84%). The inclusion of castor beans as a biodiesel feedstock in the B5 scenario, however, resulted in a significantly higher participation of family scale farms in the biofuel production sector as compared to the other CP scenarios (Figure 7). These results support the Brazilian Government biofuel policy, in which two of the main goals are the use of castor beans and the generation of on farm jobs through the promotion of biodiesel production [21]. According to our estimations, the inclusion of castor beans in the NER biodiesel feedstock pool would imply the transfer of additional R$ 20 million of federal government subsidies to the NER region, once current farm gate price for this feedstock is below the brake-even price required by Brazilian biodiesel plants.

Two final comments are noted here. First, the four CP scenarios in this study propose a significant expansion in annual cropland use, namely a 32% increase when compared to current (2007) NER annual cropland allocation, from 11.04 to 14.58 million ha. The achievement of this new annual cropland allocation depends on continuing agricultural productivity increase and at the same time, on the adoption of better practices in agriculture and soil management and conservation. Moreover, continuous drought risk has severely impacted the NER agriculture production and productivity in the past. In this paper, the optimization model does not explicitly consider this risk factor, and this certainly can be improved in future versions. The fact that the NER did not present an annual crop allocation larger than 11 million ha since year 1994 (see Figure 2 above) illustrates how difficult the crop expansion projected in the CP will be for the NER.

Second, the results presented in this section indicate how intricate the agricultural feedstock production and the implications of defining feedstock allocation for different sectors can be. In this situation the decision maker (DM) encounters himself under pressure regarding which agricultural sector should receive priority and how much certain priorities will cost to the local and federal governments. For instance, the simple setting of staple food crops as a regional priority could represent significant losses to the target region in the export and biofuel sectors. In this situation the use of a multiple objective approach to search for optimized solution seems highly desirable and even mandatory. Offering a highly impartial search for optimized solutions, the use of the compromise programming (CP) technique diminishes the chances that subjective or biased DM preferences may be introduced to the solution quest. This is especially important in developing countries where policies and government are frequently overrun due to external pressures.

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Table 1

Staple food and biofuel feedstock sources and destinations tracked in the cropland allocation model (c = current; *p* = potential)

Crop	Actual and potential feedstock destinations in the model		
	Staple food	Biofuel	Export commodity
Annual crops			
1. Beans	c	-	-
2. Cassava	c	-	-
3. Castor beans	-	*p*	*c*
4. Corn	c	-	-
5. Cotton	c	-	*p*
6. Peanuts	c	*p*	*p*
7. Rice	c	-	-
8. Soybeans	c	*p*	c
9. Sugarcane	c	c	c
Perennial crops			
10. Coffee	c	-	c
11. African palm	c	*p*	*p*
12. Coconut	c	*p*	*p*
Alternative source			
13. Microalgae	-	*p*	-
Pasture land	assumed constant in the model		
Forest land	assumed constant in the model		

Table 2

Recommended and income adjusted staple diets for Brazil's NER population* [17]

Food	Recommended (per capita/day)	Income adjusted (per capita/day)
Meat**	130 g	100 g
Milk	400 ml	400 ml
Eggs	50 g	50 g
Bread	100 g	100 g
Rice	120 g	60 g
Corn meal	100 g	50 g
Beans	100 g	90 g
Vegetables***	100 g	100 g
Cassava flour	80 g	50 g
Cassava	100 g	50 g
Banana	100 g	100 g
Orange	100 g	100 g
Margarine	20 g	20 g
Vegetable oil	20 ml	20 ml
Sugar	50 g	50 g
Coffee	20 g	20 g

* Final nutritional value: lipids: 22.0 to 24.8%; carbohydrates: 61.6 to 64.0%; protein: 13.6 to 14.0%
** Includes beef, pork, poultry, goats, lam and fish
*** Vegetables: tomatoes, pumpkin and chayote ("chu chu")

Table 3

Average annual growth rate and estimated fossil fuel and biofuel demand in the NER, Brazil (based on figures presented by [19])

Fuel	Average annual growth rate	Demand (,000 boe)	
		Current	Projected
	2000 - 2006	2007	2017
Diesel	2.73%	38,524	50,429
Gasoline	2.32%	18,961	23,846
Biodiesel	0.00	770	2,294
Ethanol	5.07%	4,972	9,702
AEAC	2.32%	2,887	3,631
AEHC	11.28%	2,085	6,071

Table 4

Farm type estimated feedstock production share (%) in the NER, Brazil

(adapted from INCRA/FAO [23])

Crop	Farm type share on regional feedstock production (%)		
	Agribusiness	Family scale	Subsistence
Annual crops			
Beans	0.21	0.74	0.05
Cassava	0.18	0.77	0.05
Castor beans	0.16	0.79	0.05
Corn	0.35	0.61	0.04
Cotton annual	0.44	0.56	-
Peanuts	0.16	0.79	0.05
Rice	0.30	0.66	0.05
Soybeans	0.97	0.03	-
Sugarcane	0.93	0.08	-
Perennial crops			
African palm	0.20	0.80	-
Coconut	0.20	0.80	-
Coffee	0.77	0.23	-

Table 5

Scenarios used in the present model to evaluate the impacts of biodiesel adoption in the NER, Brazil

Characterization	Initial (2007)	Initial + 10 years (2017)				
		Baseline	CP optimized scenarios			
	Ini	Base	B5	B5+ec	B5+m	B10+m
Biodiesel adoption level	0%	0%	5%	5%	5%	10%
Biodiesel feedstock use constraint	-	-	No	Yes	Yes	Yes
Microalgae based biodiesel supply share	-	-	0%	0%	50%	50%

Table 6

Initial and baseline scenarios cropland allocation results for the NER, Brazil:

Annual cropland

Cropland allocation (,000,000 ha)	Scenarios		
	Initial (2007)	Baseline (2017)	Change
I. Total cropland allocated			
	11.043	12.807	1.764
II. Dedicated cropland			
Staple food	7.884	8.002	0.117
Biofuel	0.476	0.651	0.176
Export	2.683	4.154	1.471
III. Allocated cropland by farm type			
Agribusiness	5.344	6.751	1.408
Family scale	5.345	5.694	0.348
Subsistence	0.354	0.362	0.008

Table 7

Initial and baseline scenarios cropland allocation results for the NER, Brazil:

Perennial cropland

Cropland allocation (,000,000 ha)	Scenarios		
	Initial (2007)	Baseline (2017)	Change
I. Total cropland allocated			
	0.438	0.520	0.082
II. Dedicated cropland			
Staple food	0.172	0.202	0.031
Biofuel	0.000	0.000	0.000
Export	0.267	0.318	0.051
III. Allocated cropland by farm type			
Agribusiness	0.191	0.230	0.040
Family scale	0.248	0.290	0.042
Subsistence	0.000	0.000	0.000

Table 8

Cropland allocation impacts for the NER, Brazil: Initial (2007) and baseline (2017) scenarios

Indicator / objective	Scenarios		
	Initial (2007)	Baseline (2017)	Change
I. Regional biofuel production (% of regional demand)			
Ethanol	100%	82%	-18%
Biodiesel	0%	0%	-
II. Economic indicators (,000,000 R$)			
1. Staple food feedstock	-5,476	-6,313	-15%
2. Agriculture commodity export	2,873	6,429	124%
3. Biofuel feedstock	407	648	59%
4. Fuel balance	-3,115	-5,890	-89%
III. Regional development objectives			
1. Staple food feedstock autonomy (%)	64%	66%	4%
2. Fuel feedstock autonomy (%)	55%	38%	-31%
3. Comprehensive feedstock economic impact (M R$)	-5,312	-5,126	3%
4. Job positions @ farm level (,000 jobs)	1,153	1,257	9%

Table 9

Individual optimal results for the four objectives in the 2017 cropland allocation model, NER, Brazil (payoff matrix)*

Objective	Unit	Baseline	Max.			
			Staple food autonomy	Energy autonomy	Comprehen. balance	Jobs
Staple food autonomy	(%)	66%	**77%**	24%	59%	27%
Energy (fuel) autonomy	(%)	38%	29%	**81%**	71%	70%
Comprehensive trade balance	(,000,000 R$)	(5,126)	(2,250)	(4,351)	**59**	(217)
Job positions at farm level	(,000 jobs)	1,257	1,518	1,528	1,533	**1,538**

* diagonal elements in bold in the dotted area reflect ideal solutions for each of the objectives in the model

Table 10

Baseline and CP optimized scenarios cropland allocation results for the NER, Brazil: (2017): Annual cropland

Cropland	Baseline	CP optimized scenarios			
(,000,000 ha)		B5	B5+ec	B5+m	B10+m
I. Total cropland allocated					
	12.807	14.575	14.575	14.575	14.575
II. Dedicated cropland					
Staple food	8.002	9.386	9.400	9.406	9.411
Export	4.154	1.035	1.641	1.702	1.761
Biofuel	0.651	4.154	3.534	3.467	3.404
III. Allocated cropland by farm type					
Agribusiness	6.751	7.209	7.209	7.209	7.209
Family scale	5.694	6.935	6.935	6.935	6.935
Subsistence	0.362	0.432	0.432	0.432	0.432

Table 11

Biofuel production in baseline and CP optimized scenarios, NER, Brazil (2017) *

Biofuel (,000,000 m^3)	Baseline	CP optimized scenarios B5	B5+ec	B5+m	B10+m
I. Ethanol					
Regional production	2.068	9.101	9.046	9.025	9.006
Share on regional demand	82%	361%	359%	358%	358%
II. Biodiesel					
Regional production	-	0.693	0.480	1.001	1.523
Share on regional demand	0%	174%	120%	251%	191%
III. Biodiesel feedstock share					
Cotton annual	-	-	-	-	-
Peanuts	-	-	-	-	-
Soybeans	-	0.581	0.474	0.449	0.425
African palm	-	0.006	0.006	0.006	0.006
Coconut	-	-	-	-	-
Castor beans	-	0.107	-	-	-
Microalgae	-	-	-	0.546	1.092

* Ethanol in Brazil is produced from sugarcane only

Table 12

Regional feedstock trade balances in baseline and four CP optimized scenarios for the NER, Brazil (2017)

Economic indicator	Baseline	CP optimized scenarios			
		B5	B5+ec	B5+m	B10+m
Staple food feedstock	-6,313	-3,976	-3,948	-3,937	-3,927
Commodity export	6,429	2,499	2,892	2,943	2,991
Biofuel feedstock	648	3,413	3,135	2,226	1,318
Fuel balance	-5,890	-2,471	-2,629	-2,308	-1,987

Table 13

Baseline and CP multiple objective optimization results for four model objectives applied to the NER, Brazil (2017)

Model objectives	Baseline	CP optimized scenarios			
		B5	B5+ec	B5+m	B10+m
Comprehensive feedstock economic impact (,000,000 R$)	-5,126	-535	-549	-1,077	-1,605
Staple food feedstock autonomy (%)	66%	70%	70%	71%	71%
Fuel feedstock autonomy (%)	38%	74%	72%	76%	79%
Job positions @ farm level (,000 jobs)	1,257	1,528	1,528	1,532	1,537

Table 14

Farm land available in the NER (based on 2006 data; published in IBGE, 2009)

Region	Land use availability (,000,000 ha)			
	Permanent crops	Annual crops	Rangeland /pasture	Forest /timber
Northeast (NE)	**5.237**	**16.978**	**32.649**	**25.579**

Table 15

Total number and area occupied by three farm types in the NER (INCRA/FAO, 2000)

Farm type	Number of farms (,000,000 farms)		Farm area (,000,000 ha)	
Agribusiness	**0.311**	13%	**49.128**	61%
Family scale	**0.923**	37%	**29.571**	37%
Subsistence	**1.235**	50%	**1.830**	2%
TOTAL	**2.469**	100%	**80.529**	100%

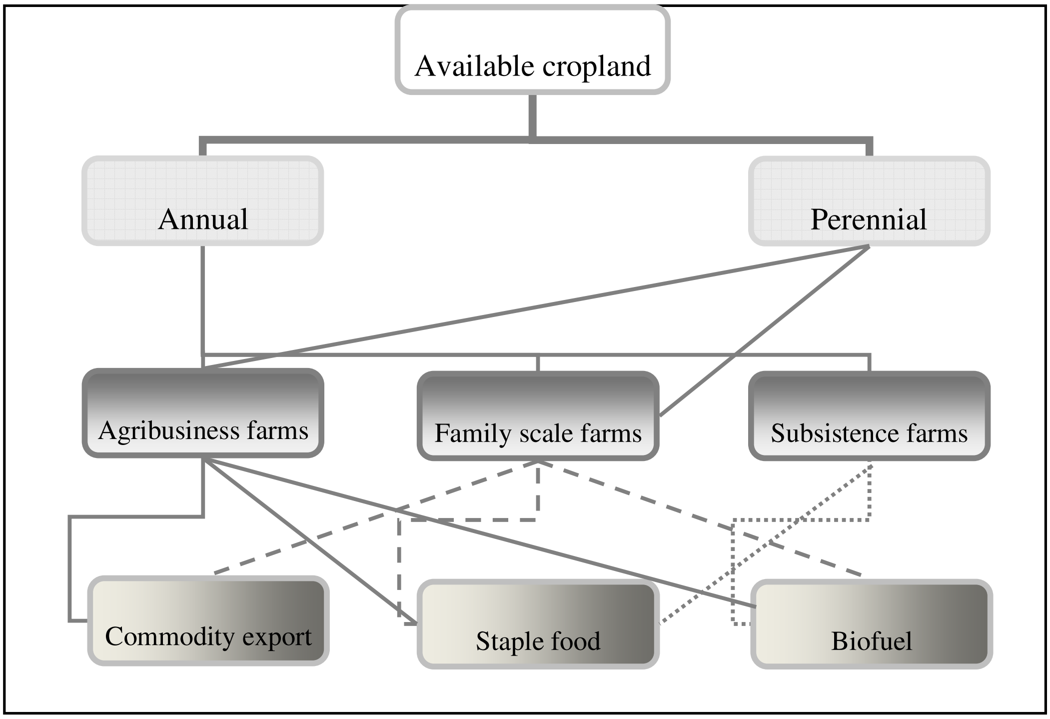

Figure 1 Simplified diagram showing the relations between available cropland, cropland use, farm type and feedstock destinations as followed in this study

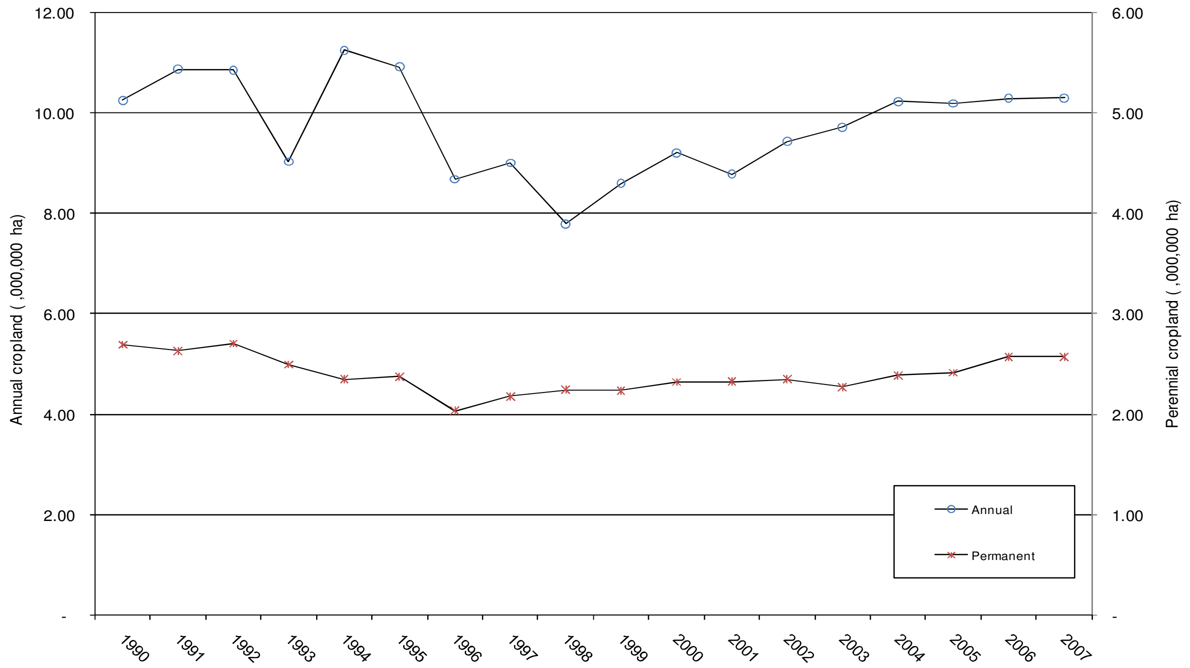

Figure 2 Historical annual and perennial cropland evolution in the NER, Brazil (IBGE, 2009)

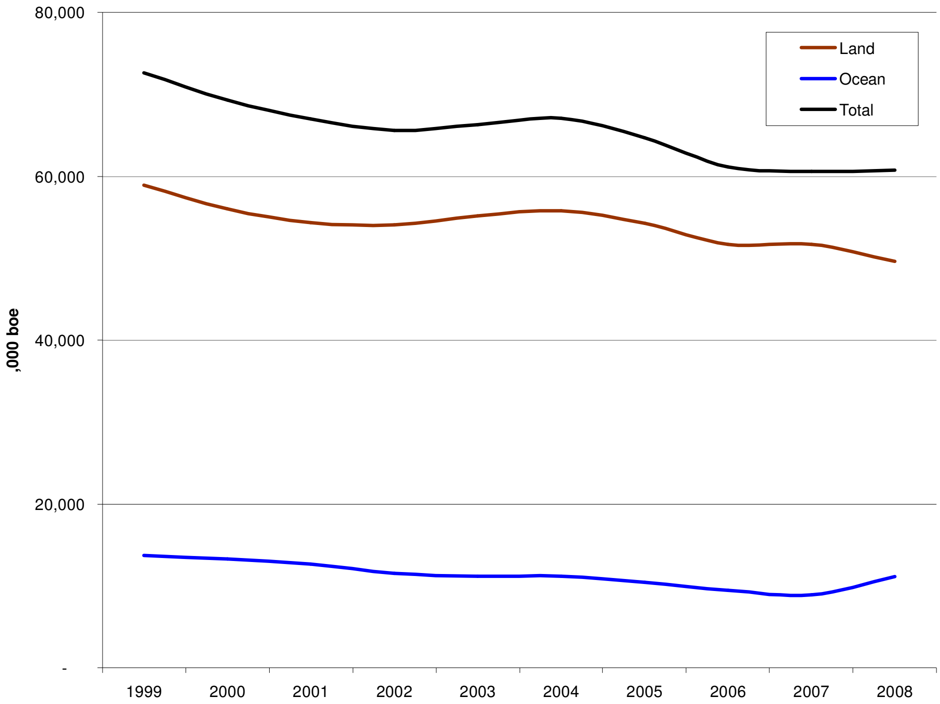

Figure 3 Petroleum extraction evolution in the NER, Brazil (ANP, 2009)

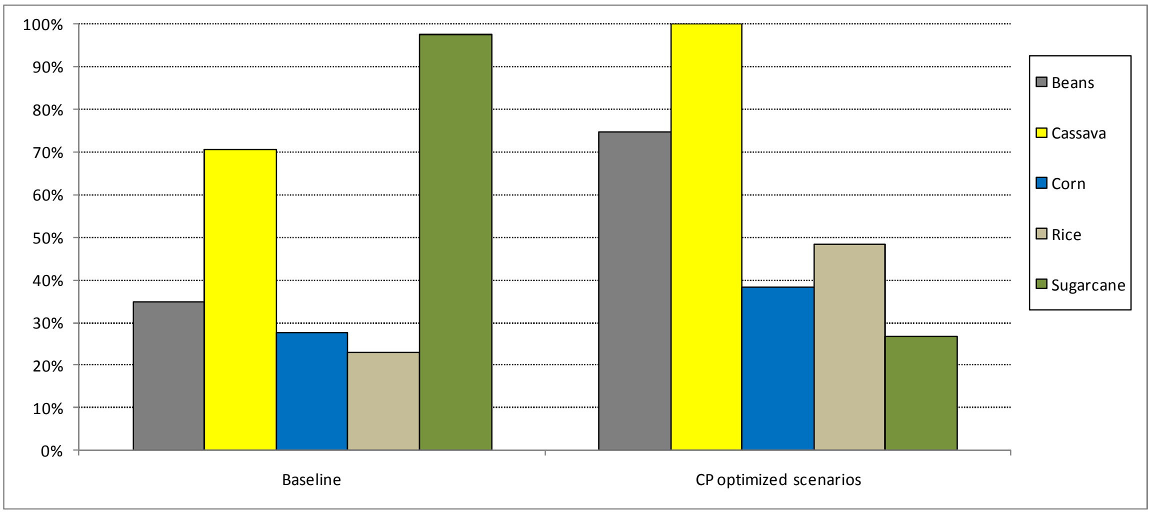

Figure 4 Average regional staple food autonomy results for selected crops in baseline and four CP scenarios, NER, Brazil (2017)

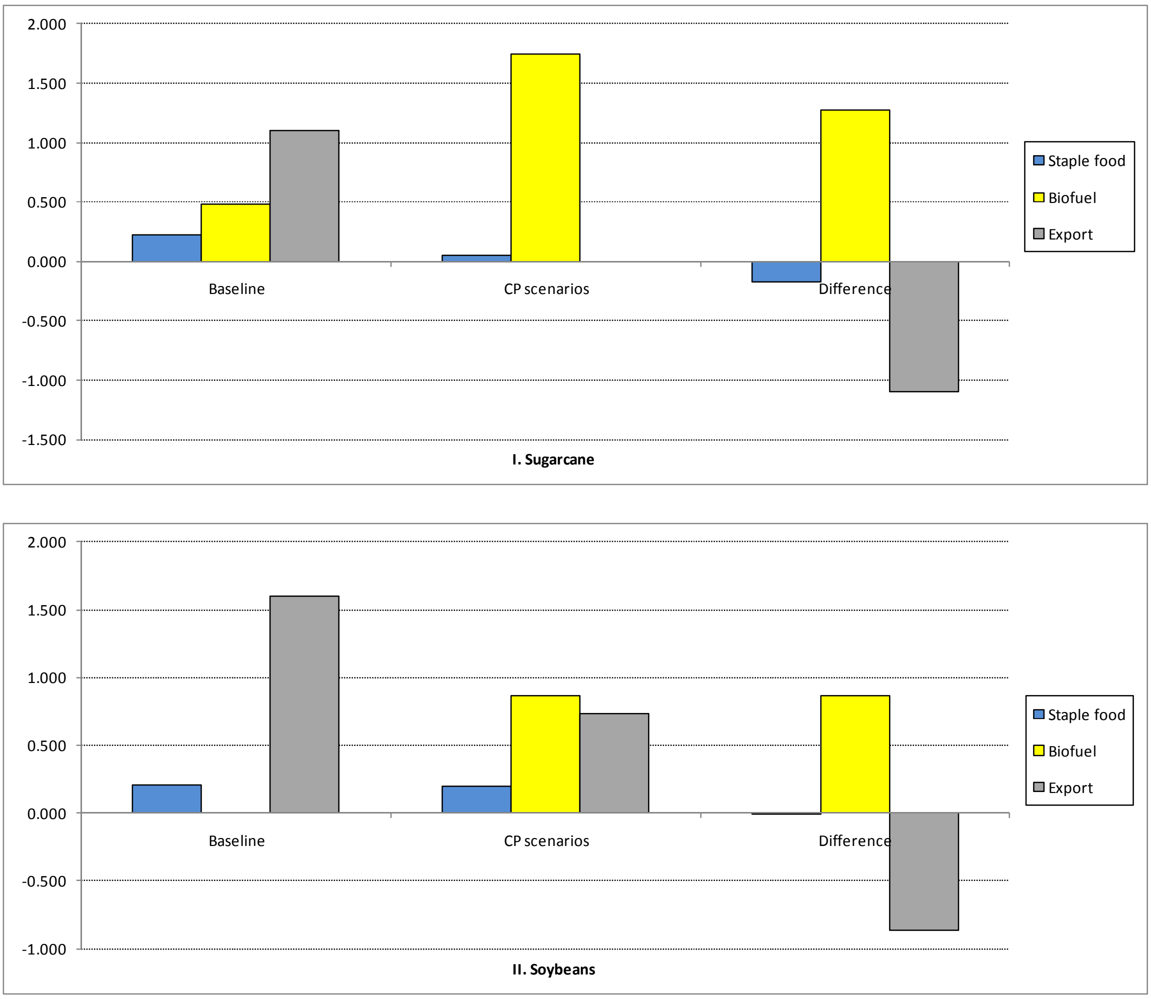

Figure 5 Average cropland allocation shifts between the baseline and CP optimized scenarios for the NER, Brazil (2017): I. Sugarcane; II. Soybeans

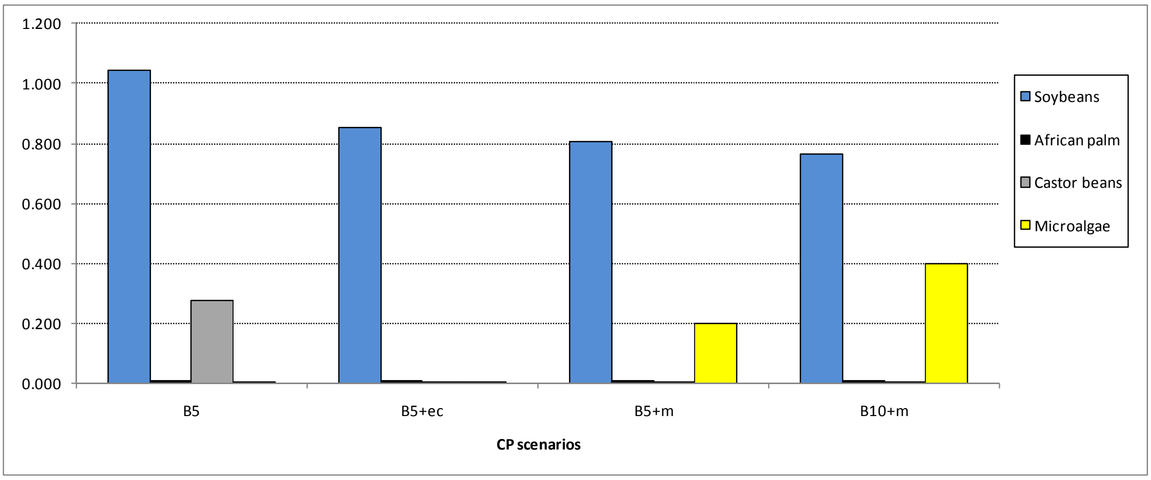

Figure 6 Biodiesel feedstock sources cropland allocations in four CP scenarios for the NER, Brazil (2017)

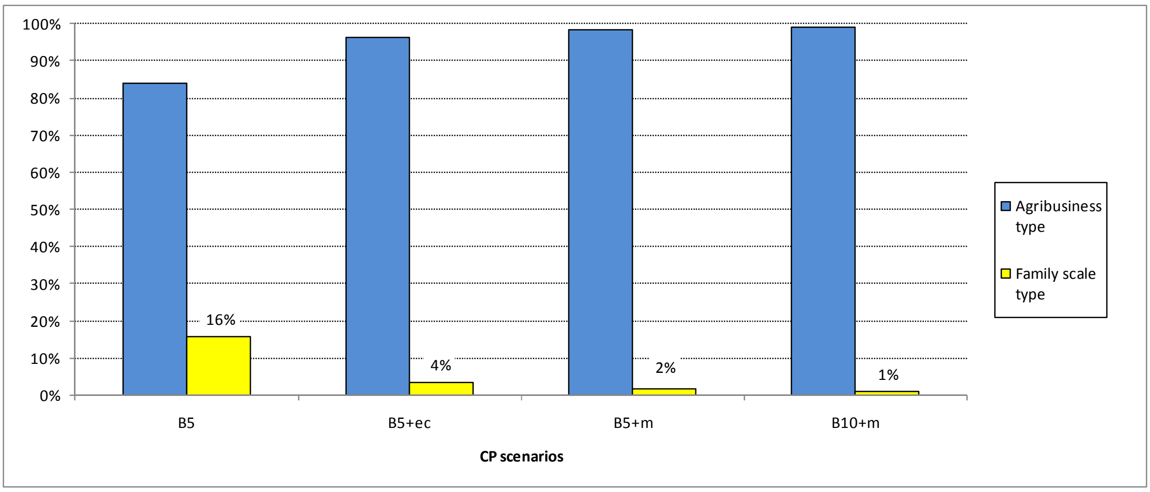

Figure 7 Farm type participation in biodiesel feedstock production in four CP scenarios outlined for the NER, Brazil (2017)