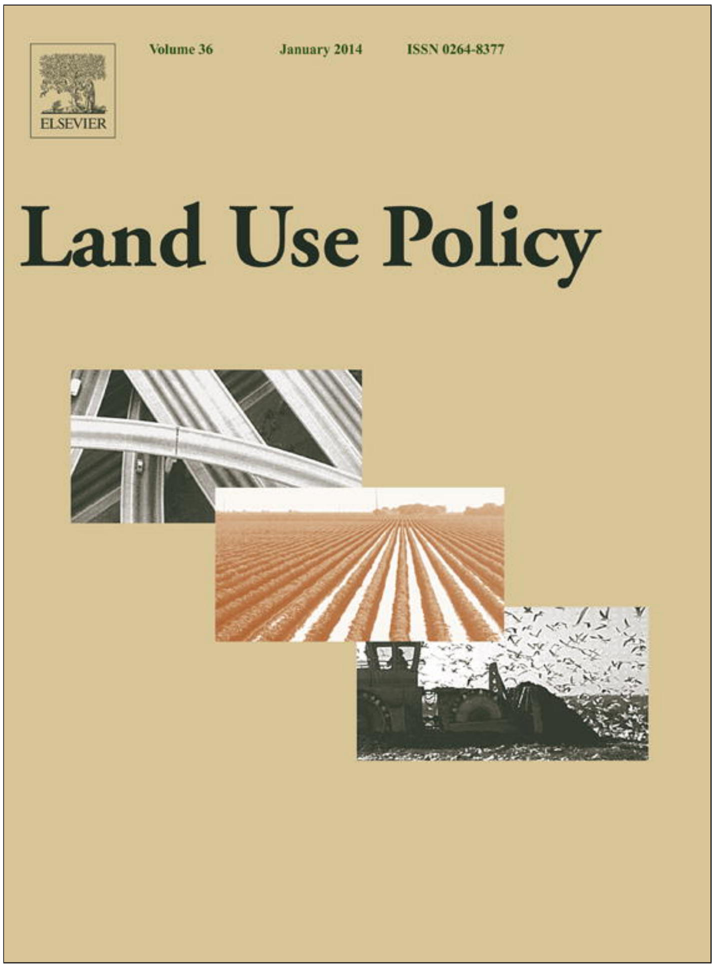
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# Ethanol expansion and indirect land use change in Brazil

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In this paper we analyze the indirect land use change (ILUC) effects of ethanol production expansion in Brazil through the use of an inter-regional, bottom-up, dynamic general equilibrium model calibrated with the 2005 Brazilian I-O table. A new methodology to deal with ILUC effects is developed, using a transition matrix of land uses calibrated with Agricultural Censuses data. Agriculture and land use are modeled separately in each of 15 Brazilian regions with different agricultural mix. This regional detail captures a good deal of the differences in soil, climate and history that cause particular land to be used for particular purposes.

Brazilian land area data distinguish three broad types of agricultural land use, Crop, Pasture, and Plantation Forestry. Between one year and the next the model allows land to move between those categories, or for unused land to convert to one of these three, driven initially by the transition matrix, changing land supply for agriculture between years. The transition matrix shows Markov probabilities that a particular hectare of land used in one year for some use would be in another use next period. These probabilities are modified endogenously in the model according to the average unit rentals of each land type in each region.

We ask whether biofuel expansion is consistent with new laws, limiting forest clearing in Brazil. A simulation with ethanol expansion scenario is performed for year 2020, in which land supply is allowed to increase only in states located on the agricultural frontier. Results suggest that each new hectare of sugar cane requires only 0.14 ha of new land, with another 0.47 ha converted from pasture use. Hence policies limiting deforestation are unlikely to prevent greater ethanol production. Finally, regional differences in sugarcane productivity are found to be important elements in ILUC effects of sugar cane expansion.



## Introduction

The worldwide expansion of biofuels production has raised concerns about its impact on food security and food supply, due to competition for agricultural land. Researchers have linked this competition to recent hikes in food prices.

In Brazil the issue is also highly controversial. Brazil is the one of the Worldís leader in ethanol production, initiating in the early 1970s a program which led to the development by local automobile companies of flex-fuel engines. Presently, around half of all Brazilian cars (and nearly all new cars) use these hybrid engines, which can run with any mixture of pure ethanol and gasohol (around 80% gasoline and 20% ethanol). In 2010 cars used nearly equal volumes of gasoline and ethanol (although diesel, used mainly by commercial vehicles, accounted for nearly 50% of transport energy use)[1].

Although the production and use of ethanol in Brazil has increased greatly in the last decade, Bacha (2009) points out that no food scarcity has arisen. On the contrary, the per capita production of fruits, agricultural raw materials, food and beverages has increased. This gain was accompanied by strong productivity increases in agriculture, as well as an increase in land use.

As is well known, Brazil still has a vast stock of land which could be converted to agricultural uses. Land clearing for agriculture is a complex and multi-dimensional phenomenon that raises great concerns. Although the rate of land clearing is now easier to measure, via satellite monitoring, its causes are much harder to assess, as pointed out by Babcock (2009), who also argues that . . . "the debate about whether biofuels are a good thing now focuses squarely on whether their use causes too much conversion on natural lands into crop and livestock production around the world". The debate is of economic importance, since regulations regarding biofuels will depend crucially on the indirect land use changes (ILUC) caused by the expansion in energy agricultural-based products.

Land use policy also interacts with bio-fuel expansion. In recent years Brazil has enacted several laws limiting further deforestation. Could biofuel expansion hinder enforcement of such laws?

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[1] See http://en.wikipedia.org/wiki/Ethanol_fuel_in_Brazil for more detail.

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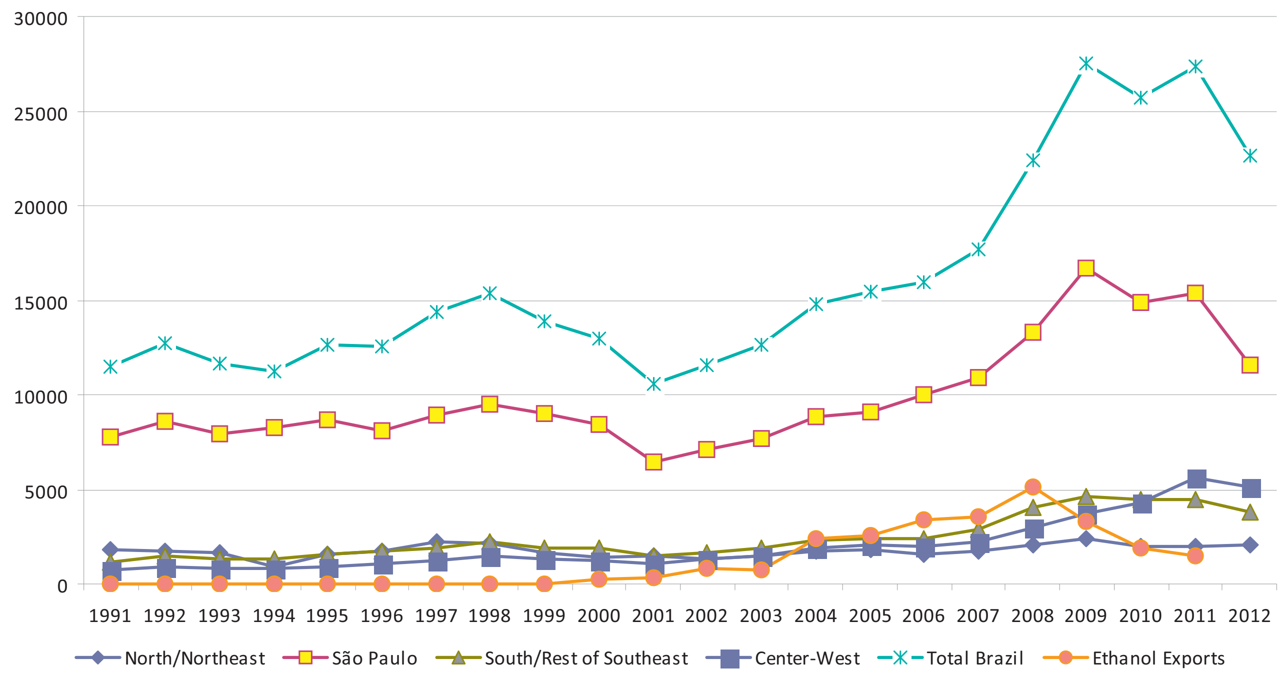


**Fig. 1.** Evolution of ethanol production and exports in Brazil (million liters).
*Source*: Secretaria de Comércio Exterior do Brasil (SECEX).

Among the studies which try to measure ILUC associated with ethanol expansion in Brazil are those of Nassar et al. (2010), Ferez (2010), and Sá et al. (2013), with different methodological approaches. The ILUC effects of other crops such as soybeans were analyzed by Lapola et al. (2010), Barona et al. (2010), Arima et al. (2011) and Macedo et al. (2012). Using a global computable general equilibrium model to simulate biofuels expansion, Taheripour et al. (2010) report broad land use changes for Brazil due to biofuels mandates in the USA and the European Union.

The CGE approach situates agriculture within a consistent description of the whole economy, which inter-relates outputs and prices for all sectors, so allowing measurement of the economy-wide benefits of biofuel expansion (or the costs of restricting such expansion). However, global CGE models, like those just mentioned, enforce some compromises. For example, data from different countries must be made consistent—which usually implies common sector definitions and data scaling. Individual country detail is lost as it is forced into the global mold.

By contrast this paper draws on a CGE model of Brazil only, which is unconstrained by the need to fit inside a global model. Hence our analysis of land use change from ethanol expansion uses the most detailed CGE model of Brazil (see Section "Methodology") and is the first, we believe, to use a fully single country, multiregional dynamic CGE model of Brazil for this purpose. In more detail the model used in this paper:

- Consists of up to 27 separate regional CGE models 2 (of each Brazilian state), linked by trade and labor movements. Such detail allows us to capture regional differences in agriculture and climate, while still reporting results according to the political regions that are of interest to policy-makers.
- Is dynamic, tracking annual changes over 2006–2020. This has many advantages, in particular allowing us to depict land use change as a process in time.
- Distinguishes four main land uses: Crop, Pasture, Planted Forestry and Other (Unused). Other CGE models distribute land between such categories according to a static CET mechanism, so that the area used for crops is a function of current prices. If Crop area goes up, this CET approach does not tell us what the previous use of the new Crop land was. Our dynamic approach uses 4 × 4 transition matrices for each region that tell how quickly land is moving between any two uses. We model these rates of land use change as a function of prices. This approach is novel within CGE modeling, and unique for CGE models of Brazil.

In summary, this paper analyzes the indirect land use changes caused by scenarios of ethanol expansion with a detailed inter-regional general equilibrium model of Brazil. To accomplish this task we propose a new method of modeling the ILUC.

## Sugarcane and ethanol expansion and land use in Brazil

Ethanol production in Brazil doubled in the period between years 1990 and 2009, and, as shown in Fig. 1, has been increasing since year 2000, reaching a peak of around 27.5 billion liters in 2009. The increase came mainly from the state of São Paulo,[2] the largest producer. Fig. 2 shows that most new sugarcane was planted in São Paulo, which in 2008 accounted for 60% of total Brazilian ethanol production. São Paulo's planted area grew from 1.8 Mha (million hectares) in 1990 to 4.9 Mha in 2008.

These figures are central to the ILUC discussion. In São Paulo and most of Brazil's Southern states, the stock of convertible land has basically run out, meaning that the supply of agricultural land is fixed. Hence sugarcane expands only at the expense of other land uses.

[2] In this paper "São Pauloȑefers always to São Paulo state, rather than to its capital city, also named São Paulo. Remaining 26 states are grouped using Brazil's system of 5 "macro-regionsȑ: **North** (Rondônia, Acre, Amazonas, Roraima, Pará, Amapá, Tocantins), **Northeast** (Maranhão, Piauí, Ceara, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia), **Southeast** (Minas Gerais, Espirito Santo, Rio de Janeiro and São Paulo), **South** (Paraná, Santa Catarina and Rio Grande do Sul), and **Center-west** (Mato Grosso do Sul, Mato Grosso and Goiás/Brasilia). These are shown in Appendix Map 1.

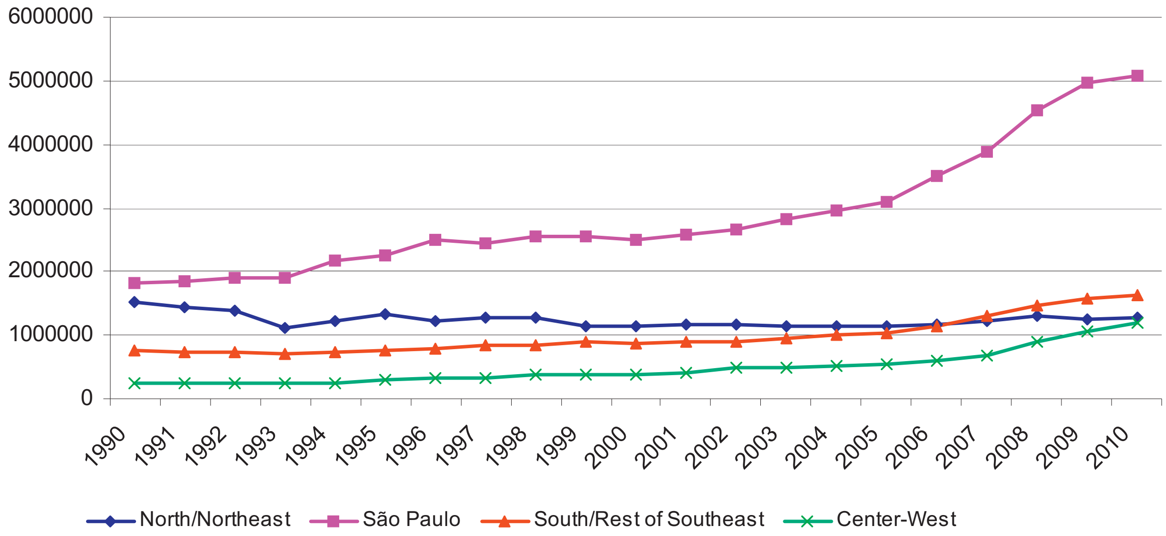


**Fig. 2.** Evolution of sugarcane planted area in Brazil, by state (hectares).

*Source*: Produção Agricola Municipal. IBGE.

However, around 12 Mha have been added to total crop area between 1995 and 2006 according to the Brazilian Agricultural Censuses of 1996 and 2006 (14 Mha between 1995 and 2009). An extra 1.8 Mha of planted pastures have been incorporated in the same period. The expansion of agricultural area has taken place mainly in some states in the Center-west, North and Northeast of Brazil, notably those closer to the Center-west Cerrados (tropical savanna) areas.

Fig. 3 shows how land use evolved between the last two Brazilian Agricultural Censuses (1995 and 2006). There, "Unused" land is defined as the total area of each state minus the used areas: crops, pastures and planted forests, as shown in each respective Agricultural Census. It includes, then, all areas not used in agriculture, like natural forests, but also urban areas, lakes and roads. These areas, however, are expected to change much less than the land-cleared areas, so the change in "Unused" is used here as a proxy for deforestation, or land clearing for agricultural uses.[3]

As seen in Fig. 3, falls in unused land occurred mostly in the states of Rondônia and Pará, in the North (Amazon) region, and in the state of Mato Grosso (which is also in the Legal Amazon). However, while in Rondônia and Pará there was a strong increase in pastures, in Mato Grosso the increase was in crops areas (which was used mostly for soybean).

We see also rises in unused land, particularly in Minas Gerais, São Paulo and Goias. We believe that these reflect, not resurgent natural forests, but rather a change in statistical classification (from 1995 rough pasture to 2006 unused). In each case the rise in unused accompanies a fall in pasture. In São Paulo, the most important sugarcane expansion region, new land stocks are (as noted above) in practice exhausted. Thus, even if adjustment is made for statistical reclassification, it is clear that in São Paulo land for sugarcane was drawn from other agricultural activities, especially from pastures.

Similarly in Paraná the 1.9 Mha increase in area under crops in the period was matched by a 1.97 Mha fall in pasture area. In the frontier state of Rondônia, on the other hand, the 1.8 Mha increase in pasture area was matched by a 1.7 Mha fall in unused land. This illustrates the complexity of analyzing the ILUC process, as noted by Babcock (2009). How much of the increase in pastures in Rondônia can be imputed to any particular crop area expansion in Southeast Brazil?

To analyze this issue, we use "transition matrices" as seen in Table 1. These matrices show in the last column the total area for each use in 1995 and in the last row the corresponding value in 2006. These totals are drawn from the IBGE Agricultural Censuses of 1995 and 2006.[4] Numbers within the table bodies are not observed but reflect an imposed prior[5]: that most new Crop land was formerly Pasture, and that new Pasture normally is drawn from

**Table 1**
Total land use change matrix, 1995–2006 (Mha).

| | Crop | Pasture | Plant forest | Unused | Total 1995 |
|---|---|---|---|---|---|
| *São Paulo* | | | | | |
| Crop | 5.4 | 0.0 | 0.0 | 0.4 | 5.8 |
| Pasture | 1.4 | 6.8 | 0.0 | 0.9 | 9.1 |
| Plant forest | 0.0 | 0.1 | 0.3 | 0.1 | 0.6 |
| Unused | 0.0 | 0.0 | 0.0 | 9.3 | 9.3 |
| Total 2006 | 6.8 | 6.9 | 0.4 | 10.7 | 24.8 |
| *Mato Grosso* | | | | | |
| Crop | 3.5 | 0.0 | 0.0 | 0.0 | 3.5 |
| Pasture | 3.7 | 17.7 | 0.0 | 0.0 | 21.5 |
| Plant forest | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 |
| Unused | 0.8 | 4.0 | 0.1 | 60.4 | 65.3 |
| Total 2006 | 8.0 | 21.8 | 0.1 | 60.4 | 90.3 |
| *Brazil* | | | | | |
| Crop | 44.8 | 1.1 | 0.0 | 4.9 | 50.8 |
| Pasture | 15.5 | 146.0 | 0.6 | 15.6 | 177.7 |
| Plant forest | 0.1 | 0.9 | 3.5 | 0.9 | 5.4 |
| Unused | 1.0 | 10.9 | 0.4 | 605.3 | 617.6 |
| Total 2006 | 61.4 | 158.9 | 4.5 | 626.7 | 851.5 |

*Source*: original data from IBGE.

3 Miranda et al. (2005) estimated that the total urbanized area in Brazil in 2000 was 21,285 km$^2$, or just 0.25% of the total Brazilian territory in year 2000. Only 12% of that total is located in the Legal Amazon region (that comprises our definition of agricultural frontier, nine states and 56% of the Brazilian territory).

4 The Brazilian Agricultural Census of 1996 has as references the periods between August, 1, 1995 and July, 31, 1996. The 2006 Agricultural Census has as reference the year of 2006 (IBGE, available at http://www.ibge.gov.br/home/estatistica/economia/agropecuaria/censoagro/brasil_2006/default.shtm).

5 This prior is based on field observation, since it is usually difficult to have agriculture immediately after land clearing, due to the huge amount of the original vegetation roots on the soil, which prevents mechanical operations; and chemical characteristics of soils, that have to be prepared for agriculture. This is according to

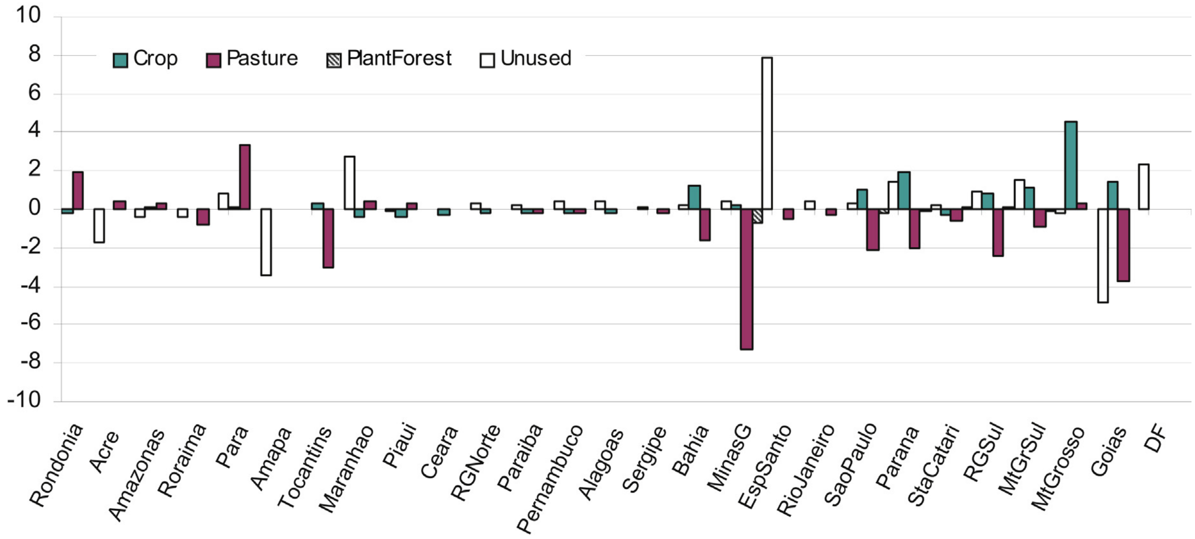


**Fig. 3.** Land use change in Brazil, by state. Variation between 1995 and 2006.
*Source*: Brazilian Agricultural Censuses 1995 and 2006.

Unused land. The prior estimates are scaled to sum to the data-based row and column totals. The off-diagonal values in the body of the table are the transition (calibrated) between those two periods, and show the amount of each land category which is transformed to another. Although the table only covers São Paulo, Mato Grosso and all Brazil, the model data contains values for all the other states.

Table 1 shows that the total crop area in 1995 was around 50.8 Mha, changing to 61.4 Mha in 2006. These figures were drawn from the respective Brazilian Agricultural Censuses. In the period about 15.5 Mha of pastures were converted to crops, while just 1.0 Mha were directly converted from unused land to agriculture. It can also be seen that for the period the total area under pastures has decreased from 177.7 to about 158.9 Mha.[6]

However, the land use transition differed markedly between states. While in São Paulo virtually no unused land was converted for any other use in the period, in Mato Grosso (on the agricultural frontier) about 840 thousand hectares were directly converted from unused to crop, and 4 Mha to pastures. This information, by state, will be used later to generate a transition matrix which will show the annual rate of change (or conversion) of each use to the other, and is the basis for our transition matrix modeling of land use change.

## Methodology

In this paper we use a multi-period computable general equilibrium model of Brazil, based on previous work by Ferreira Filho and Horridge (2011), to analyze the ILUC effects of projected sugarcane expansion. The model includes annual recursive dynamics and a detailed bottom-up regional representation, which for the simulations reported here distinguished 15 aggregated Brazilian regions (see Appendix Map 2). It also has 38 sectors, 10 household types, 10 labor grades, and a land use change (LUC) model which tracks land use in each state, to be described below. The core database is based on the 2005 Brazilian Input–Output table. The model features an ethanol/gasohol substitution module, as used by Ferreira Filho and Horridge (2009).

The model's recursive dynamics consist basically of three mechanisms: (i) a stock-flow relation between investment and capital stock, which assumes a 1-year gestation lag; (ii) a positive relation between investment and the rate of profit; and (iii) a relation between wage growth and regional labor supply. With these three mechanisms it is possible to construct a plausible base forecast for the future, and a second, policy, forecast—different only because some policy instruments are shocked to different values from the base (e.g., the ethanol expansion scenarios). This difference can be interpreted as the effect of the policy change. The model is run with the aid of RunDynam,[7] a program to solve recursive-dynamic CGE models.

### Modeling regional land use

Increased production of biofuels may arise from technical progress, or by using more inputs, such as capital, labor or land. The last of these, land, is in restricted supply. Some fear that to produce more biofuels Brazil may need to divert land from other crops, raising food prices, or convert unused land to agriculture at the expense of the environment. Others claim that sugarcane acreage could be doubled, without much affecting land available for other crops. To assess these claims, our CGE model needs to model land use explicitly, as described in this section.

To begin we emphasize that agriculture and land use are modeled separately in each of 15 Brazilian regions with different agricultural mix; and, clearly, land cannot move between regions. This regional detail captures a good deal of the differences in soil, climate and history that cause particular land to be used for particular purposes.

Table 2 is drawn from the model database and shows land used by agricultural industry in São Paulo (specializing in sugar and citrus), Mato Grosso (soybeans and beef cattle), and the whole of Brazil, in year 2005. Nationwide, around 60% of agricultural land is used for beef cattle grazing.

Brazilian land area statistics by the Instituto Brasileiro de Geografia e Estatísticas (IBGE) distinguish 3 types of agricultural land use, Crop, Pasture, and Plantation Forestry. We assumed that

findings in Nassar et al. (2010), Arima et al. (2011), Brown et al. (2005), Morton et al. (2006) and Barona et al. (2010).

[6] This includes planted and natural pastures.

[7] RunDynam is part of the GEMPACK economic modeling software (Harrison and Pearson (1996)).

**Table 2**
Land used by agriculture in Brazil, 2005 (Mha).

| | São Paulo | Mato Grosso | Brazil | Land type |
|---|---|---|---|---|
| Rice | 0 | 0.9 | 3.9 | Crop |
| Corn | 1.1 | 1 | 11.6 | Crop |
| Wheat | 0.1 | 0 | 2.9 | Crop |
| Sugarcane | 3.1 | 0.2 | 5.8 | Crop |
| Soy | 0.8 | 6.1 | 23 | Crop |
| Fruit veg | 0.6 | 0.2 | 8.6 | Crop |
| Cassava | 0 | 0.1 | 2 | Crop |
| Tobacco | 0 | 0 | 0.5 | Crop |
| Cotton | 0.1 | 0.5 | 1.3 | Crop |
| Citrus | 0.6 | 0 | 1 | Crop |
| Coffee | 0.2 | 0 | 2.3 | Crop |
| Forestry | 0.4 | 0.1 | 4.7 | Planted forest |
| Beef cattle | 5.6 | 20.8 | 136.4 | Pasture |
| Dairy | 1.5 | 0.9 | 24.1 | Pasture |
| Total agriculture | 14.1 | 30.9 | 228.1 | |
| Unused | 10.7 | 59.4 | 623.4 | |
| Total | 24.8 | 90.3 | 851.5 | |

*Source*: interpolated from Brazilian Agricultural Censuses of 1995 and 2006.

each industry mapped to one of these types, as shown in the last column of Table 2.

Within each region, the area of "Crop" land in the current year is pre-determined. However, the model allows a given area of "Crop" land to be re-allocated among crops according to a CET-like rule:

$$A_{jr} = \lambda_r \cdot K_{jr} \cdot R_{jr}^{0.5}$$

where $A_{jr}$ is the area of crop land in region $r$ used for industry $j$, and $R_{jr}$ is the unit land rent earned by industry $j$.[8] $K_{jr}$ is a constant of calibration while the slack variable $\lambda_r$ adjusts so that:

$$\sum_j A_{jr} = A_r = \text{pre-determined area of crop land.}$$

The same mechanism is used to distribute Pasture land between Beef and Dairy uses. Forestry land has only one use.

The final row of Table 2 shows the total area of each region—which considerably exceeds the amount used for agriculture. The difference, called "Unused", accounts for 73% of Brazil's total area. It should include land used for cities and other housing, roads and road verges, rivers and their banks, land too steep, dry or swampy to use, environmental reserves, and many other uses. It also includes land which could be used for crops or grazing, but is not yet so used. The North and West of Brazil contain large areas both of cultivable savanna and of forests that could be felled for grazing.

Between one year and the next the model allows land to move between the Crop, Pasture, and Forestry categories, or for unused land to convert to one of these three. Based on the information displayed in Table 1 (which shows land use changes between 1995 and 2006), a transition matrix approach is used, as illustrated in Table 3. As before, we show extracts for São Paulo (around the size of UK), Mato Grosso (France + Germany), and the whole of Brazil (non-Alaskan USA). These one-year transition matrices show land use changes in the first year of our simulation. Row labels refer to land use at the start of a year, column labels to year end. Thus the final, row-total, column in each sub-table shows initial land use, while the final, column-total, row shows year-end land use. Within the table body, off-diagonal elements show areas of land with changing use.

Above, row totals reflect the 2005 values shown in Table 2. Column totals relate to row totals using the average rate of change

[8] Keeney and Hertel (2008) use the same 0.5 exponent, which they attribute to the FAPRI model.

**Table 3**
One-year transition matrices for land use change (Mha).

| | Crop | Pasture | Planted forest | Unused | Total 2005 |
|---|---|---|---|---|---|
| *São Paulo* | | | | | |
| Crop | 6.4 | 0.1 | 0 | 0.1 | 6.6 |
| Pasture | 0.4 | 6.6 | 0 | 0.1 | 7.1 |
| Plant forest | 0 | 0.1 | 0.3 | 0 | 0.4 |
| Unused | 0 | 0.1 | 0 | 10.6 | 10.7 |
| Total 2006 | 6.7 | 6.9 | 0.4 | 10.8 | 24.8 |
| *Mato Grosso* | | | | | |
| Crop | 8.7 | 0.2 | 0 | 0.1 | 9 |
| Pasture | 1 | 20.6 | 0 | 0.1 | 21.8 |
| Plant forest | 0 | 0.1 | 0 | 0 | 0.1 |
| Unused | 0 | 0.9 | 0.1 | 58.4 | 59.4 |
| Total 2006 | 9.7 | 21.8 | 0.1 | 58.7 | 90.3 |
| *Brazil* | | | | | |
| Crop | 59.2 | 1.6 | 0 | 2 | 62.9 |
| Pasture | 5 | 153 | 0.4 | 2.1 | 160.5 |
| Plant forest | 0 | 0.9 | 3.6 | 0.1 | 4.7 |
| Unused | 0.1 | 3.7 | 0.6 | 619 | 623.4 |
| Total 2006 | 64.3 | 159.2 | 4.6 | 623.3 | 851.5 |

*Source*: derived from Tables 1 and 2, assuming constant growth rates over 11 years.

of land use during the last 11 years (see Table 1). Numbers within the table bodies are not observed but reflect an imposed prior: that most new Crop land was formerly Pasture, and that new Pasture normally is drawn from Unused land. The prior estimates are scaled to sum to the data-based row and column totals.

The transition matrices could be expressed in share form (i.e., with row totals equaling one), showing Markov probabilities that a particular hectare used today for, say, Pasture, would next year be used for crops. In the model, these probabilities or proportions are modeled as a function of land rents, via:

$$S_{pqr} = \mu_{pr} \cdot L_{pqr} \cdot P_{qr}^{\alpha} \cdot M_{qr}$$

where (the $r$ subscript always denoting region):

$S_{pqr}$ = share of land type $p$ that becomes type $q$ in region $r$.

$\mu_{pr}$ = a slack variable, adjusting to ensure that $\sum_q S_{pqr} = 1$.

$L_{pqr}$ = a constant of calibration = initial value of $S_{pqr}$.

$P_{qr}^{\alpha}$ = average unit rent earned by land type $q$.

$\alpha$ = a sensitivity parameter, with value set to 0.35.

$M_{qr}$ = a shift variable, initial value 1.

The sensitivity parameter $\alpha$ was set to 0.35 to give a "normal" (close to observed) past evolution of crops areas in the baseline.

Thus, if Crop rents rise relative to Pasture rents, the rate of conversion of Pasture land to Crops will increase. To model the rate of conversion of Unused land we needed to assign to it a fictional rent—we chose the regional CPI. However, in our scenarios we only allowed the amount of Unused land to decrease in selected frontier regions, namely Rondonia, Amazon, ParaToc, MarPiaui, Bahia, MtGrosso, and Central. In the other, mainly coastal regions, total agricultural land was held fixed (by endogenizing the corresponding $M_{qr}$ variable).

In summary, the model allows for, say, sugarcane, output to increase through:

- assumed uniform primary-factor-enhancing technical progress of 1.5% p.a. (baseline assumption)[9];

[9] Notice that this is an assumption that reflects historical productivity increases in Brazilian agriculture. This assumption is incorporated both in the baseline and in the policy simulations, and as such is not a source of extra sugar cane production in the policy simulation.

- increasing non-land inputs[10];
- using a greater proportion of Crop land for sugarcane, in any region;
- converting Pasture land to Crops, if Crop rents increase, in any region; and
- converting Unused lands to Pasture or Crop uses, in frontier regions.

The last three mechanisms above characterize the indirect land use change (ILUC) examined in this paper.

The transition matrix proposed in this paper, then, represents a summary of the multiple variables that can affect deforestation, and which are incorporated in the differential rates of transition between different types of land use. The proposed regional level of disaggregation allows taking into account local effects, such as soil types and institutional arrangements, which might affect the easiness of expanding deforestation in a particular region, and which might be caused by variables other than the economic ones which typically drive results in a CGE model. Our approach, then, departs from other approaches in the literature in the sense that, instead of trying to directly measure the ILUC, we make use of the informational contents conveyed by the transition matrices together with economic theory to try to get insight about that phenomenon. The advantage of this method is that all the economic effects involved can be tracked in detail in the modelís structure, and correlated to the ILUC effects.

## Model baseline and scenario simulation

As stated before, the model database is for year 2005. The model was run for three years of historical simulations, using observed data to update the database to 2008, followed by annual simulations to simulate the ethanol expansion scenario until 2020. The baseline assumes moderate economic growth until 2020, around 3.5% increase in real GDP per year, with projections for population increase by state from IBGE.

To analyze the ILUC effects of an aggressive expansion of ethanol production, we compare a moderate scenario with a more aggressive one, analyzing the differences in land use in both situations. With this in mind, the baseline projections for ethanol entail a moderate expansion in exports as well as in household use, around 4% per year. These projections result in an equivalent 4% per year increase in ethanol production in Brazil.[11]

The policy scenario, on the other hand, is based on the projections by EPE[12] (2008), and comprises a 12.8% per year increase in ethanol exports, from 2008 to 2020, and a 9.2% per year increase in household use of ethanol, in the same period. No endogenous technological change was considered for the simulations.

## Closure

The model closure allows labor to move between regions and activities, driven by real wages changes, but not to move between labor categories.[13] Capital accumulates between periods driven by profits, as discussed before. Real government spending increases by 3% p.a. in all regions. Nationally, household consumption follows GDP[14]; the national total is distributed between regions in proportion to labor income. In order to mimic expected sugarcane expansion, a few other closure rules were used in the simulations:

- Capital in the ethanol industry was allowed to accumulate only in some regions, where ethanol expansion is expected to occur (Ferreira Filho and Horridge, 2009). These regions are Minas Gerais (MinasG), São Paulo, Parana, Mato Grosso do Sul (MtGrSul), Mato Grosso (MtGrosso) and Central.
- In the policy scenario, exports of agricultural raw products, food, textiles and mining were kept fixed at base simulation levels.

## Results

In what follows we first present the model baseline for land use in Brazil until 2020, generated by our projections for the economy and by our transition matrix approach. The corresponding policy scenario (with ethanol expansion) is described in Section "Policy results".

## Baseline results

Our baseline scenario, shown in Fig. 4, entails a 4.1% fall in unused land, accumulated in 2020, matched by a 13.2% increase in area for crops, 10.6% increase in area for pastures, and 7.3% increase in area used for planted forests. This represents an extra 25.6 Mha coming from unused land to the production of crops (8.3 Mha), pastures (16.9 Mha) and planted forests (0.34 Mha). These baseline projections, of course, result from our projections for the expansion of the Brazilian economy until 2020, as explained before, and the "normal" rate of land use change observed in the past, as expressed by our transition matrix.[15]

In regional terms, the bulk of the fall in unused land occurs in the Brazilian deforestation frontier: Mato Grosso (−12.4 Mha), Paratoc (Pará and Tocantins states, −5.9 Mha) and Rondonia (−2.9 Mha). The states of Maranhão and Piaui (MarPiaui region), agricultural frontiers in the savanna region, also present a significant fall in unused land, −2.0 Mha by year 2020.

## Policy results

The simulated increase in ethanol use and exports led to a 14.8% increase in sugarcane production above the baseline, in year 2020. This increase happens at the expense of other agricultural outputs, which are slightly reduced, as seen in Table 4. Livestock-related activities increase production slightly due to capital attraction in those activities, since exports of meats were fixed in the closure. Notice that an endogenous increase in productivity is also implied in the simulation, since production increases despite the fall in land use in the activity.[16]

[10] Production functions are of the nested CES type. Both äggregate primary factoränd äggregate intermediate inputäre demanded in proportion to output. The elasticity of substitution between primary factors was set at 0.25 for agriculture (1 for manufacturing). The elasticity of substitution between intermediate inputs was set to 0.3. There is additional substitution between different sources of a given input commodity.

[11] The observed expansion in ethanol exports in Brazil in the historical simulation period, from 2005 to 2008 it was much higher, around 25% per year.

[12] Empresa de Pesquisas Energéticas – EPE is a public company in the Ministry of Mining and Energy of Brazil which does research to support the Brazilian Energy Planning.

[13] For details, see Ferreira Filho and Horridge (2010). National supply of each labor type follows population, which is exogenous. The database contains matrices showing movement of workers between regions. If real wages in region A rise 1% relative to wages in region B, labor migration from B to A rises 3%.

[14] It turns out that our assumptions about absorption imply that the ratio, Balance of Trade/GDP, is more or less fixed. The model does not distinguish direct taxes or transfer payments, so we cannot directly observe or fix government budget deficits.

[15] We have, however, restricted the expansion of agricultural areas only to the expansion regions, as explained before.

[16] Livestock intensification, or any type of exogenous primary factor saving technological change occurring in any of the land using activities, would reduce

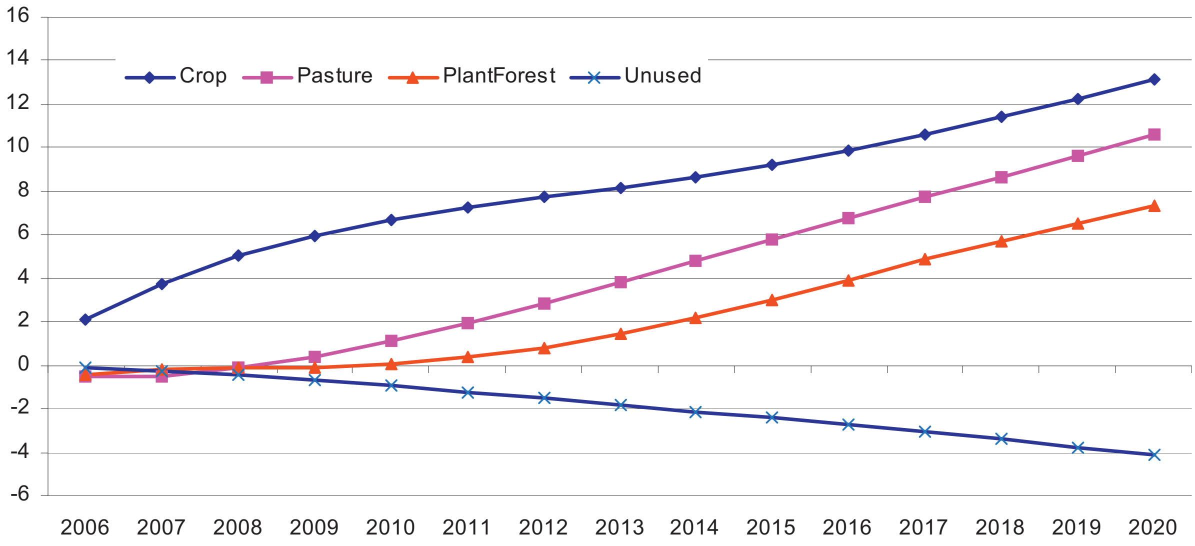


**Fig. 4.** Baseline evolution of broad categories of land use in Brazil. Percent variation, accumulated.

*Source*: model results.

**Table 4**
Changes in national agricultural production and land use, cumulative percent deviation from baseline, 2020.

| Agricultural product | (1) Production | (2) Land use ($\alpha = 0.35$) | (3) $\alpha = 0.175$ | (4) $\alpha = 0.7$ |
|---|---|---|---|---|
| Rice | 0.10 | −0.34 | −0.47 | −0.21 |
| Corn | −0.26 | −1.28 | −1.60 | −0.89 |
| Wheat | −1.46 | −2.09 | −2.36 | −1.72 |
| Sugarcane | 14.81 | 8.17 | 7.31 | 9.19 |
| Soybean | −0.04 | −0.86 | −1.14 | −0.52 |
| Other agric | −0.65 | −1.67 | −2.01 | −1.24 |
| Cassava | 0.03 | −0.71 | −0.93 | −0.45 |
| Tobacco | 0.13 | −0.37 | −0.47 | −0.27 |
| Cotton | −0.26 | −0.73 | −1.03 | −0.39 |
| Citrus fruits | −0.65 | −2.98 | −3.58 | −2.20 |
| Coffee | −0.01 | −1.10 | −1.44 | −0.73 |
| Forestry | −0.51 | −0.73 | −0.45 | −1.05 |
| Livestock | 0.03 | −0.30 | −0.20 | −0.41 |
| Raw milk | 0.06 | −0.37 | −0.24 | −0.50 |
| Other livestock | 0.10 | 0 | 0 | 0 |

*Source*: model results. Columns 3 and 4 are alternate versions of (2), computed using different $\alpha$ values—see below in Section "Sensitivity of results to assumptions".

Through competition in the primary factor markets, the expansion in sugarcane area would take land from other agricultural activities. The projected variation in each land use can also be seen in column (2) of Table 4. To match the expansion in sugarcane area the other agricultural activities reduce their area, compared to the baseline.

The all-Brazil results in Table 4 are aggregates of results computed separately for each of the model's 15 regions, which specialize in different crops. Further, labor is imperfectly mobile between regions, and we allowed only some (frontier) states to convert unused land. A full explanation of results must draw on these regional differences. For example, citrus fruit area reduces the most, since this activity is located mostly in São Paulo, the main sugarcane producer. With total land supply fixed in this (non-frontier) state, the sugarcane expansion must attract land from other uses.

Some agricultural outputs increase despite the fall in land use. For example, rice production increased by 0.1% relative to the baseline, despite the 0.34% fall in its area. The reason is that rice is produced in regions where the competition with sugarcane is not as intense as, say, in the case of corn. Only 23% of total rice production in the base year is produced in the sugarcane expansion region. Actually, most of the rice (about 55%) is produced in Rio Grande do Sul state (in the SCatRioS aggregate) which produces almost no sugarcane. Corn, on the other hand, has about 74% of total production in the expansion area, in the base year. Following the price increases in the simulation, rice is able to attract more capital and labor from other activities than corn, increasing its production.

Another interesting case is raw milk production. This activity also increases production, despite the fall in land use in aggregate. It is a regional effect associated with the expansion of sugarcane in Brazil's most important milk state, Minas Gerais. Sugarcane is much less labor intensive than most of other agricultural activities. This is particular true for the new expansion regions, like Minas Gerais. The sugarcane expansion, then, frees up labor for the remaining activities, benefitting most the more labor intensive ones. Besides that, the second largest milk producing state is Santa Catarina, which is not in the expansion area, and has productivity by hectare higher than Minas Gerais. The increase in milk prices and the reduction in labor wages in milk production stimulate supply in this region, increasing production at the new prices.

Notice that while sugarcane production increases 14.8% by the end of the period, its land use increases less, by 8.17%. The reason is that sugarcane is expanding in regions with higher productivity than the Brazilian average. São Paulo, the state with the highest sugarcane productivity in Brazil, is where sugarcane expands the most, as shown in Fig. 5. This effect is relevant for the ILUC discussions regarding sugarcane expansion, since the higher is the productivity of the expanding culture the smaller is the land displacement required, for each unit of product.

As discussed before, the main interest of this paper is on the ILUC effects of the ethanol expansion in Brazil. For this purpose we have computed the overall land use change, according to broad land areas categories caused by the ethanol expansion, by state. Here, however, we present only the national aggregates. The evolution of broadly defined land use variation caused by the ethanol expansion scenario can be seen in Fig. 6.

Model results show that a 0.75% expansion in crops area would be required by 2020, to accommodate the simulated ethanol expansion scenario. Pasture land would fall by 0.21%, Planted forest land by 0.65%, and Unused land by 0.02%. In physical terms this would

deforestation through the reduction in the requirement of land for each unit of production.

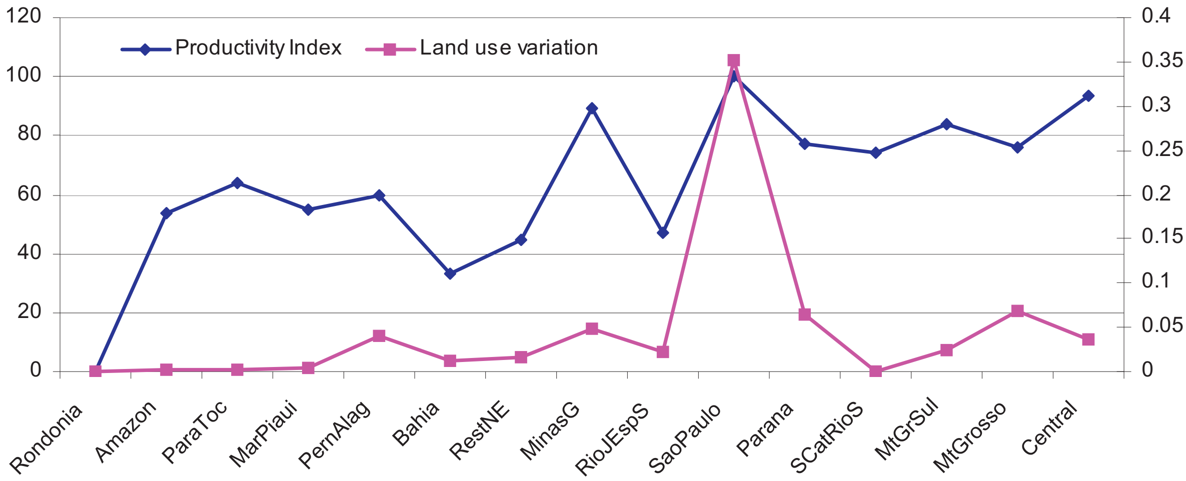


**Fig. 5.** Sugarcane area variation (% accumulated in 2020) and productivity index, by region.
*Source*: land use variation: model results. Productivity: basic data from IBGE.

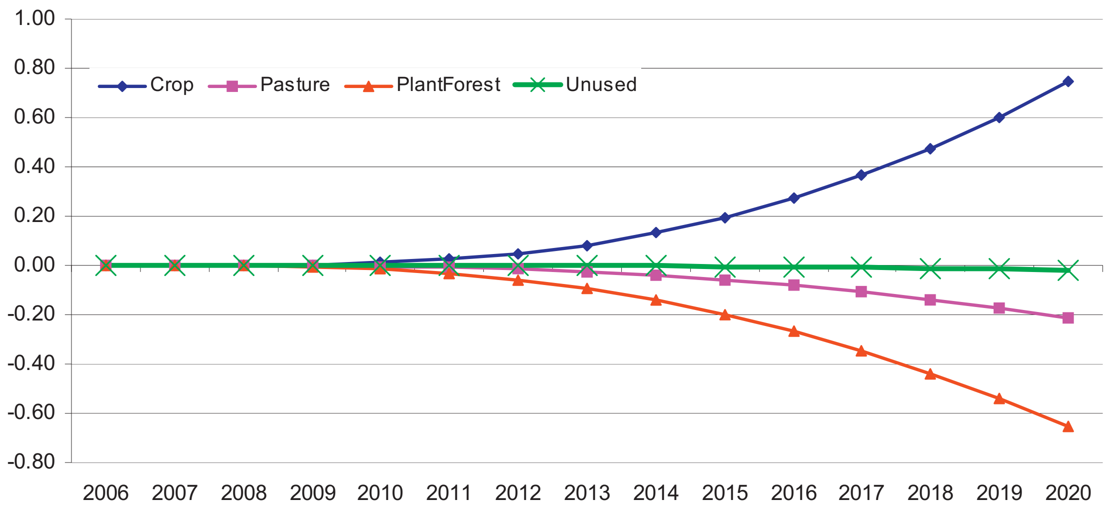


**Fig. 6.** Simulation results. Land use variation in Brazil. Cumulated percent deviation from base.
*Source*: model results.

account for an extra 530 thousand hectares of crops,[17] and a reduction of 380 thousand hectares of pastures, 30 thousand hectares of planted forests, and 120 thousand hectares of unused land.

Nassar et al. (2010), in a study about the relation of sugarcane expansion and land use change in Brazil with physical data for the period 2005–2008, concluded that the ILUC caused by sugarcane was around 8%, meaning that for each extra hectare of sugarcane in the period only 0.08 ha of new land, or deforestation, was observed in Brazil as a whole. Our results allow the same type of calculation, shown in Fig. 6, which shows the period average of the ratio of the change in sugarcane area and the change in unused or pastures areas.

Table 5 above shows that, over the period considered[18] each extra sugarcane hectare was associated with a 0.14 ha fall in unused land, and with a 0.47 ha fall in pastures. Our model's projected ILUC, then, is somewhat higher than the one reported by Nassar et al. (2010).

Our reported value for ILUC above is an average for the period, but our dynamic model generates yearly values, which evolve over time. These ILUC values change monotonically from −0.014 in 2009 to −0.268 in 2020, averaging −0.14. This happens because of regional differences in sugarcane land productivity, as discussed before. As sugarcane expands in São Paulo (the state with higher productivity), attracting land from other uses, the price of land starts to increase faster, making this substitution harder. This makes the rate of cane expansion higher in areas where the productivity is smaller, increasing the land area required for each ton of sugarcane. In the end, this process causes an increasing ILUC. Fig. 7 graphs the simulated rate of expansion of sugarcane area for the

**Table 5**
Simulation results. Average ILUC in Brazil.

| | Ratio of area change |
|---|---|
| Unused/sugarcane | −0.14 |
| Pastures/sugarcane | −0.47 |

*Source*: model results.

[17] Sugarcane itself would require 680 thousand hectares more, but it would attract land from other activities, reducing the total requirement of crop land.
[18] i.e., 2008–2020, since the 2005–2007 simulated period was just the historical simulations for database updates.

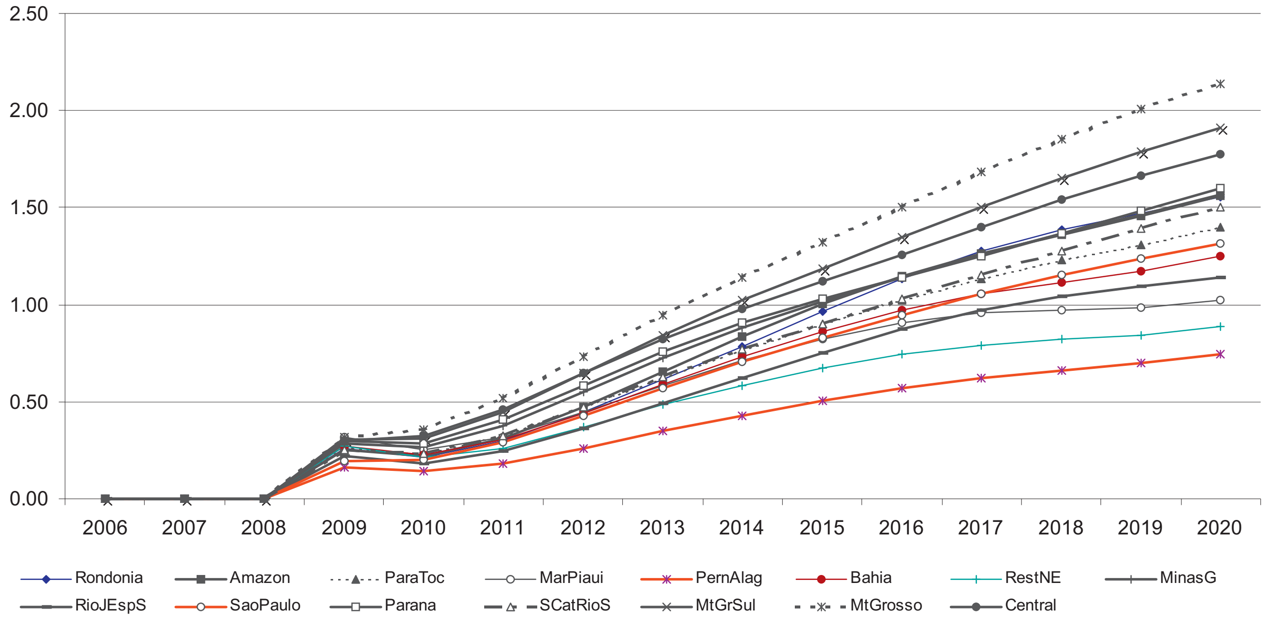


**Fig. 7.** Model results. Sugarcane land use by region. Cumulative percent deviation from base.

*Source*: model results.

main cane-growing states in Brazil. It shows that sugarcane area grows less fast in São Paulo (the state with the higher productivity) than in several other states.

Of course, this happens in the simulations because we have kept productivity fixed across years. But this sheds light on the importance of productivity increases for the biofuels-deforestation issue. The higher the productivity increases the smaller the amount of new land necessary to match a given increase in biofuels production. At the same time, ILUC associated with sugarcane expansion would be reduced if the expansion into new areas is accompanied by productivity increases.

## Sensitivity of results to assumptions

A CGE model like that used here builds on a host of assumptions; about functional forms; about assumed elasticity values; and about initial data. Rarely do we have a probability distribution which measures the uncertainty of estimates that are fed in—so we cannot in general compute probability distributions for model outputs. We can however merely report how results depend on input values.

To present results for many alternate possible specifications would consume much space, but we do here present partial results for 2 alternate estimates of the sensitivity parameter $\alpha$ (see Section "Modeling regional land use") which relates land use change to land rents. The alternate results correspond to a halving and a doubling of our central 0.35 value, and are shown in the last two columns of Table 4. The acreage results are positively related to $\alpha$, but the sensitivity is not marked. Our intuition is that the $\alpha$ value becomes less important as the number of time periods increases.[19]

## Final remarks

Biofuel expansion has raised concern worldwide, especially in the light of recent food price increases. The diversion of land previously used in food production toward energy crops is considered to be one factor behind those food price hikes. Our simulation, however, shows that this is not the case in Brazil. With the projected "normal" rate of increase in land supply at the agricultural frontier the amount of new land required for sugarcane production would be relatively small, and the same is true for the fall in other crops or livestock production. The rate of ILUC found here, although higher than that found by previous studies, cannot be considered very high: only 0.14 ha of extra land would be required for each extra sugarcane hectare. Hence, biofuel expansion is not necessarily inconsistent with regulations that limit forest clearing.

Another very important point arises from our results, relating to agricultural productivity. As shown, the expansion of sugarcane in the region with higher agricultural productivity actually saves land, in relative terms. However, it is expected that land prices will increase due to this attraction, fostering sugarcane expansion in the new regions. The average productivity in those regions was shown to be higher than in some traditional regions, but smaller than in São Paulo. This sheds light on an important topic for public policies, since the higher the productivity gains in sugarcane production, the smaller will be the ILUC effect. Agricultural research policies, then, important as they are in the general context of food security, can also be regarded as important instruments to reduce ILUC effects of biofuels expansion.

[19] The reader could assess other dependencies of model results on inputs, as the model and simulations used in this paper are downloadable: see item TPMH0130 at http://www.monash.edu.au/policy/archivep.htm.

## Appendix A. Regions of Brazil


Map 1: 27 states and 5 macro-regions of Brazil

*Note*: maps are scaled to enlarge areas at bottom and right (so Amazon looks smaller)


Map 2: 15 regions used for simulation

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