Mitig Adapt Strateg Glob Change
DOI 10.1007/s11027-008-9164-3

ORIGINAL ARTICLE

Environmental, land-use and economic implications of Brazilian sugarcane expansion 1996–2006

Gerd Sparovek · Alberto Barretto · Goran Berndes · Sergio Martins · Rodrigo Maule

Received: 19 June 2008 / Accepted: 30 October 2008

Abstract Governments are promoting biofuels and the resulting changes in land use and crop reallocation to biofuels production have raised concerns about impacts on environment and food security. The promotion of biofuels has also been questioned based on suggested marginal contribution to greenhouse gas emissions reduction, partly due to induced land use change causing greenhouse gas emissions. This study reports how the expansion of sugarcane in Brazil during 1996–2006 affected indicators for environment, land use and economy. The results indicate that sugarcane expansion did not in general contribute to direct deforestation in the traditional agricultural region where most of the expansion took place. The amount of forests on farmland in this area is below the minimum stated in law and the situation did not change over the studied period. Sugarcane expansion resulted in a significant reduction of pastures and cattle heads and higher economic growth than in neighboring areas. It could not be established to what extent the discontinuation of cattle production induced expansion of pastures in other areas, possibly leading to indirect deforestation. However, the results indicate that a possible migration of the cattle production reached further than the neighboring of expansion regions. Occurring at much smaller rates, expansion of sugarcane in regions such as the Amazon and the Northeast region was related to direct deforestation and competition with food crops, and appear not to have induced economic growth. These regions are not expected to experience substantial increases of sugarcane in the near future, but mitigating measures are warranted.

Keywords Ethanol · Sugarcane · Brazil · Land use change · Pastures · Deforestation · Environment

G. Sparovek (✉) · A. Barretto
University of Sao Paulo/Esalq, Av. Pádua Dias, 11, CEP 13418-900 Piracicaba, SP, Brazil
e-mail: gerd@usp.br

G. Berndes
Chalmers University of Technology, Gothenburg, Sweden

S. Martins · R. Maule
Entropix Engineering, Piracicaba, Brazil

Published online: 20 November 2008

1 Introduction

Concern about human induced climate change, together with escalating oil prices and the uncertainty about sustained oil supplies, has resulted in a large interest in finding alternatives to petroleum based fuels. Several countries have set targets for substituting diesel and gasoline by biofuels, with proportions ranging from 5 to 20%, to be met at various times within the coming decades (OECD 2008). The consequent changes in agricultural land-use and reallocation of crops to biofuels production have raised concerns about impacts on environment and food security (RFA 2008). There are also objections referring to stated marginal—or even negative—contribution of biofuels to climate change mitigation (Pimentel and Patzek 2005). The net energy output of biofuels as well as the contribution to climate change mitigation has long been debated. Diverging conclusions in different studies can often be explained by differences in methodological approaches—for instance in allocation methods and system boundaries—and also in assumptions about critical parameter values (see, e.g., Börjesson (2008) and Farrell et al. (2006) for the case of cereal ethanol and Crutzen et al. (2008) for an account of the impact of nitrous oxide (N_2O) emissions on the climate benefit of biofuels).

Further complicating the matter, the expansion of biofuel crop cultivation requires land conversion and can also induce indirect land use change (LUC). Studies have shown that this can substantially influence the climate benefit of biofuels production and use (Leemans et al. 1996; Fargione et al. 2008; Gibbs et al. 2008; Searchinger et al. 2008). In some cases the establishment of bioenergy plantations will simultaneously enhance the biospheric carbon (C) stocks, such as when perennial grasses or short rotation woody crops are established on C-depleted lands. In other cases it may lead to lower biospheric C stocks, such as when a forest is clear cut to make place for the cultivation of soybean (Glycine max) for biodiesel or when pastures with high C content are ploughed and cultivated with cereals for ethanol (Marland and Schlamadinger 1997; Schlamadinger et al. 2001; Berndes and Börjesson 2002; Guo and Gifford 2002; Fargione et al. 2008; Gibbs et al. 2008; Searchinger et al. 2008).

The quantifications of the effects of LUC reported so far have been based on combining classical life cycle assessment (LCA) or Well-to-Wheel approaches with either prescribed land conversion patterns (e.g., Marland and Schlamadinger 1997; Fargione et al. 2008) or model projections of LUC (e.g., Leemans et al. 1996; Searchinger et al. 2008). Combining LUC and LCA models involves methodology challenges and a substantial degree of uncertainty since the possible variation of critical parameters is large. Especially the possibility that the establishment of bioenergy plantations leads to indirect LUC, potentially causing large carbon dioxide (CO_2) emissions (Laurance 2007), presents a challenge for research relating to the integration between the social, economic and spatial sciences at different scales, with the connection between micro-level behavior of individuals and macro-level structures. Several land cover data sets derived from satellite observations are available for C cycle modeling but challenges exist related to uncertainties and the fact that the data were not produced with the primary aim to support such modeling (Jung et al. 2006).

In this article, results are presented from an assessment of the expansion of sugarcane (Saccharum sp) in Brazil during the period 1996–2006. Data from the Municipal Agricultural Production (Produção Agrícola Municipal, PAM) survey and the recently finished Brazilian National Agrarian Census 2006 is compared with the 1995/96 Census (see Table 1 Endnotes for data sources). The studied period, during which no specific governmental regulation or certification procedure applied on the

Table 1 Proxy variables selected for the assessment

Variable	Description[a]	Period	Dimension	Source[b]
ScHar_06	Sugarcane in the municipality	2006	% of municipal area	IBGE—Produção Agrícola Municipal (PAM)
AnInc_ScHar_97_06	Increase of sugarcane in the municipality	1997 to 2006	% y^{-1}	IBGE—Produção Agrícola Municipal (PAM)
GDP_05	Municipal Gross Domestic Product (MGDP)	2005	R$ 10^{3} per municipality	IpeaData
AnInc_GDP_99_05	MGDP increase	1999 to 2005	% y^{-1}	IpeaData
For_06	Forest area in farm land (Census area)[2)]	2006	% of farm area	IBGE—Censo Agropecuário 2006
Dif_For_06_96	Forest area difference in farm land (2006 minus 1996)	1996 to 2006	% y^{-1}	IBGE—Censo Agropecuário 1995/96 and 2006
OtCrHar_06	Other crops area in the municipality	1997 to 2006	% of municipal area	IBGE—Produção Agrícola Municipal (PAM)
AnInc_OtCrHar_97_06	Other crops increase in the municipality	1997 to 2006	% y^{-1}	IBGE—Produção Agrícola Municipal (PAM)
Past_06	Pasture in farm land (Census area)[c]	2006	% of farm area	IBGE—Censo Agropecuário 2006
Dif_Past_06_96	Pasture area difference in farm land (2006 minus 1996)	1996 to 2006	%	IBGE—Censo Agropecuário 1995/96 and 2006
Dens_Cat_06	Cattle head density in the municipality	2006	heads km^{-2} of municipality	IBGE—Produção Pecuária Municipal (PPM)
AnInc_Cat_97_06	Cattle head increase	1997 to 2006	% y^{-1}	IBGE—Produção Pecuária Municipal (PPM)

[a] The annual increase rates were calculated by log-linear regression using the minimum square method and the annual data of each considered period

[b] Brazilian Institute for Geography and Statistics (IBGE) coordinates most of the collection of the data used (IBGE 2008a, b, c, d; Ipedata 2008)

[c] The Census area is the area covered by the Agrarian Census that includes only farmland (large extensions of natural forests, conservation reserves, urban areas and land-use types not used for agricultural production are not included in the agrarian Census surveys)

sugarcane sector, involved a substantial sugarcane expansion in Brazil—from an area of 4,814,084 ha to 6,144,286 ha, i.e., an expansion of 1,330,202 ha.

Besides investigating the environmental, land-use and economic implications of the recent sugarcane expansion, the study provides a basis for a more effective and less conjectural way of predicting the impact of an expected future expansion in Brazil. Based on the identified effects of the sugarcane expansion during the period 1996–2006, conclusions are drawn and suggestions for future research and policy are made.

2 Methodology

2.1 Scale considerations

Sugarcane is not the major land use in Brazil (e.g., pastures, soybean and corn (Zea mays) occupy approximately 25, 4 and 3 times more land, respectively). Due to the relatively low land claim of sugarcane in Brazil, the local effects of the sugarcane expansion over a period of 10 years were not perceptible based on aggregated national data. However, the effects on LUC, environment and economy were sufficient to be detected at the municipal level. For the purpose of this study, the municipal level was therefore chosen as a suitable scale for the analyses.

2.2 Identification of sugarcane expansion areas

For identification of sugarcane expansion areas and considering Brazilian municipalities of 2005, the following variables and selection criteria were used:

1. Sugarcane Relevance, given as the area cultivated with sugarcane in 2006 (**SR**, ha);
2. Presence of an industrial facility for sugarcane ethanol and/or sugar production (sugarcane mill) in the municipality (**M**, yes or no); and
3. Sugarcane Increase, represented by the annual mean rate of increase in harvested sugarcane area in the municipality during the studied period 1996–2006 (**SI**, %).

The above variables and criteria were used in a selection procedure for separating municipalities where sugarcane is not a significant crop, or where expansion occurred at slow rates (**ScNoEx**), from the municipalities where sugarcane expansion and relevance were driving factors behind LUC during the considered time period (**ScEx**). Municipalities were considered as belonging to the **ScEx** category if all of the three criteria below were met:

1. **SR** in the municipality was greater than 5,000 ha in 2006
2. **SI** during the period 1997 to 2006 was greater than 2.5 %
3. the municipality had a sugarcane mill in 2007 (**M** = yes)

Municipalities were also considered as belonging to the **ScEx** category, despite absence of a mill in 2007, if both of the two criteria below were met:

1. **SR** in the municipality was greater than 7,000 ha in 2006
2. **SI** was greater than 5%

The rationale for having higher **SR** and **SI** in this case was that if there is a mill in the municipality, even small areas of sugarcane expansion is with quite high confidence related to the mill operation. If there is no mill in the municipality, sugarcane may be expanding for other purposes such as animal feed, organic sugar and cachaça production. Thus the thresholds were increased in order to reduce the risk of sample contamination by municipalities where sugarcane was cultivated for other purposes.

Mean values were calculated and significance of differences were tested after removal of outliers and inconsistent values that could potentially bias mean and deviation values, or

compromise the accuracy of the selection procedure described above. A technical description of this further data processing is available in "Appendix 1".

2.3 Geographical grouping of municipalities

Because of large regional differences in environmental conservation, land use patterns, and economic development, **ScEx** can not be compared with **ScNoEx** on an aggregated level. The regional differences would simply dominate over the effects of sugarcane expansion. Therefore, sub-groups of comparable neighboring **ScNoEx** municipalities were defined for each **ScEx** municipality, and the **ScEx** municipalities were then compared with this neighboring sub-group in the subsequent assessment of the environmental, land use and economic effects of the sugarcane expansion.

For analytical reasons, and in order to further control the effects of regional differences, the analyzed municipalities were also divided into two main geographical groups:

- Central Expansion Area (**CEA**) defined as the expansion that occurred radiating from the present main production region (State of São Paulo and neighboring States)
- Peripheral Expansion Area (**PEA**), i.e., all other expansion areas, which moving clockwise from CEA are composed of: (i) the South Amazonian border region in Mato Grosso; (ii) the isolated initiative in the Municipality of Presidente Figueiredo in the State of Amazonas; (iii) the expansion at the East border of the Amazon (Pará and Maranhão); (iv) small expansion spots in the traditional Northeastern production region (Sergipe, Alagoas and Pernambuco) and the North part of Bahia; and (v) the North part of Espírito Santo (Atlantic Forest biome).

PEA was further divided into two groups: (i) **PEA-Am** containing municipalities within the Amazon Administrative Region according to Brazilian federal law 1.806/06.01.1953; and (ii) **PEA-NoAm** containing municipalities located outside the Amazon Administrative Region.

2.4 Selection and comparison of proxy variables

In order to investigate environmental, land use and economic implications of the sugarcane expansion, a number of proxy variables were selected to reflect the state and dynamics of environment, land use, and local economy during the studied period 1996–2006 (Table 1). The selection reflected the requirement that the proxy variables should:

- be comprehensive and available for the total area of **ScEx** and **ScNoEx** municipalities
- be systematically collected by official agencies

The values for the selected proxy variables for the years 1996 and 2006 were collected for all **ScEx** and neighboring **ScNoEx** municipalities and each **ScEx** was then compared with its own specific subgroup of neighboring **ScNoEx** municipalities. The differences between **ScEx** and neighboring **ScNoEx** municipalities were then attributed to the sugarcane expansion, based on the presumption that the only major difference between the compared municipalities was that the **ScEx** municipality experienced a significant expansion of sugarcane plantations while the neighboring **ScNoEx** municipalities did not.

3 Results

3.1 Outcome of the selection and geographical grouping of municipalities

The outcome of the selection procedure is shown in Fig. 1a,b. 136 municipalities (2.4% of all 5,564 Brazilian municipalities) were selected as belonging to the **ScEx** category. As can be seen in Fig. 1a, the expansion area of sugarcane was concentrated to a relatively small share of the Brazilian municipalities. By setting the threshold **SR** >=5,000 for

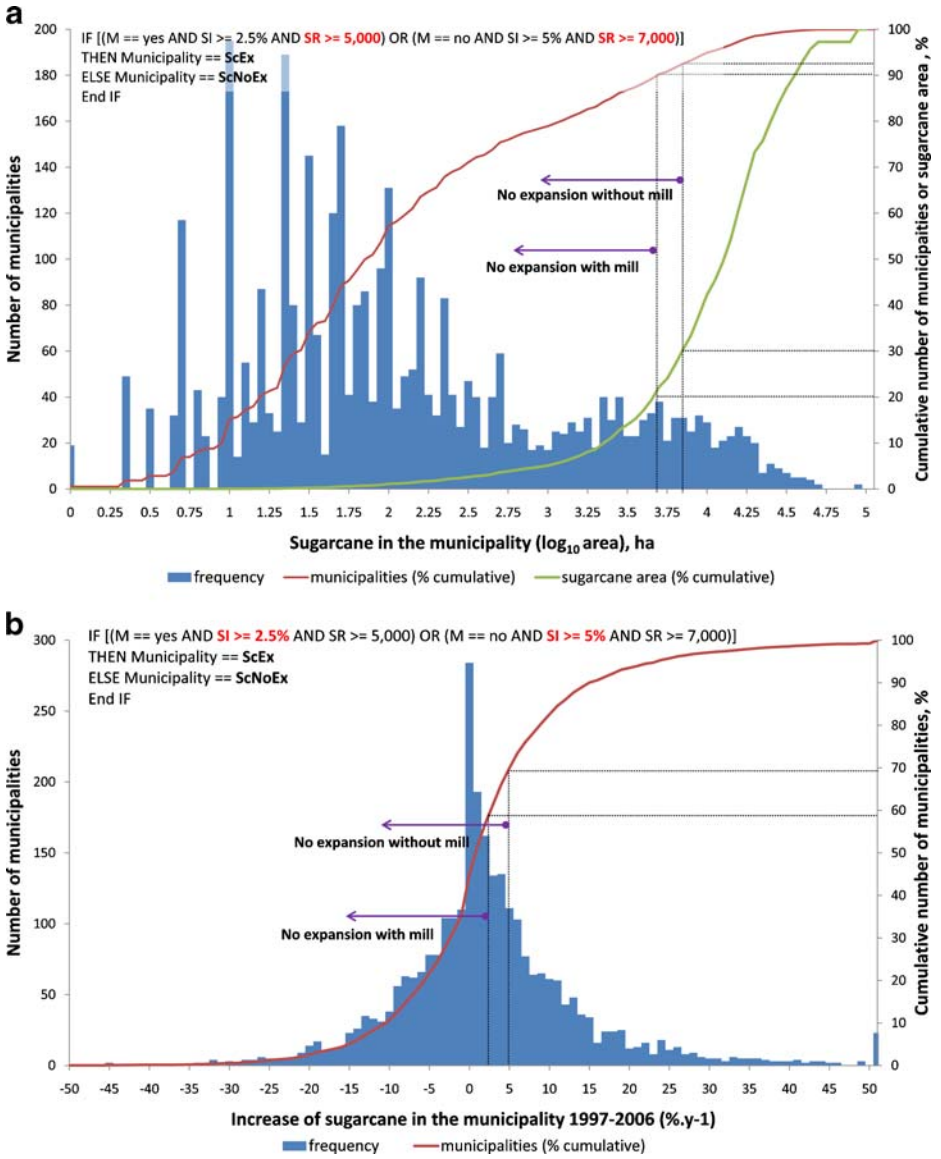

Fig. 1 Effects of threshold values for **SR** (a) and **SI** (b) in separating **ScEx** and **ScNoEx** municipalities. The Boolean expression corresponds to the selection criteria used

municipalities with a mill, about 10% of the 3,616 municipalities where sugarcane was cultivated in 2006 were selected as belonging to the **ScEx** category. However, the total area of sugarcane in **ScEx** was above 80% of the total sugarcane area in the whole of Brazil and the **ScEx** municipalities contained about 73% of the total expansion of sugarcane that occurred during the studied period 1996–2006.

The sugarcane increase rate, **SI** (Fig. 1b) as individual criterion excluded about 60–70% of the municipalities from the **ScEx** category. Considering the logic of the of the selection procedure, the asymmetric distribution of the area of sugarcane in the municipalities (highly concentrated in a small region), and the selected threshold values for **SR** and **SI**, the judgment is that the separation of **ScEx** and **ScNoEx** was effective. The significantly larger sugarcane area and sugarcane increase rates in **ScEx** compared to **ScNoEx** also confirm this. Contamination effects may always occur at the borders of the classes, but will have little effect on the final mean values, and means tests, because the differences in the criteria selected for defining the expansion concept (presence of mill, **SR** and **SI**) were large between **ScEx** and **ScNoEx**.

In the subsequent geographical grouping of municipalities, 407 **ScNoEx** municipalities were selected to be compared with the 136 **ScEx** municipalities. Figure 2 shows the results of the procedure for selection of **ScEx** and neighboring **ScNoEx** municipalities, and the subsequent geographical grouping into **CEA** and **PEA** areas. The areas of sugarcane predominance in 1995 are also shown. **CEA** includes 87% of the **ScEx** municipalities (118 of 136) and about 90% of the analyzed sugarcane expansion area (873,934 ha out of 965,837 ha). **CEA** can therefore be considered as representative of the dominating sugarcane regions in Brazil and the sugarcane expansion in Brazil for the period 1996 to 2006. **PEA** contains a relatively small total sugarcane area but includes important biomes such as the Amazon and the poor Northeast region. The development in **PEA** can therefore provide information about the implications of sugarcane expansion in non-traditional regions.

3.2 Results of the analysis based on proxy data assessment

The results of the comparison between **ScEx** and neighboring **ScNoEx** municipalities are presented for **CEA** in Table 2 and for **PEA**, separated into the two groups **PEA-Am** and **PEA-NoAm**, in Table 3.

3.2.1 Environment

In **CEA**, the area of forests on farmland (environment proxy variable) was similar in **ScEx** and **ScNoEx** (about 10% in 2006), with small increases during the period 96–06. Thus, sugarcane expansion did not induce increased direct deforestation. However, the average area of forests on farmland is noteworthy low in both **ScEx** and **ScNoEx**. Brazilian environmental legislation for this region requires that farmers keep 20% of their area as a natural reserve and the riparian areas (usually 10–15% of the farm area) also have to be protected by forests. Thus, the forest area is substantially below the legal requirements. The fact that **ScEx** and **ScNoEx** had similarly low forest areas indicates that historic agricultural expansion has caused the forest scarcity in this traditional agricultural region, rather than the recent sugarcane expansion specifically.

In **PEA-Am** direct deforestation (average 12% reduction of forests on farmland) was observed in **ScEx** during the period of 1996 to 2006, while forest area remained stable in **ScNoEx** (1.6% forest area increase on farmland). The average farmland areas covered by

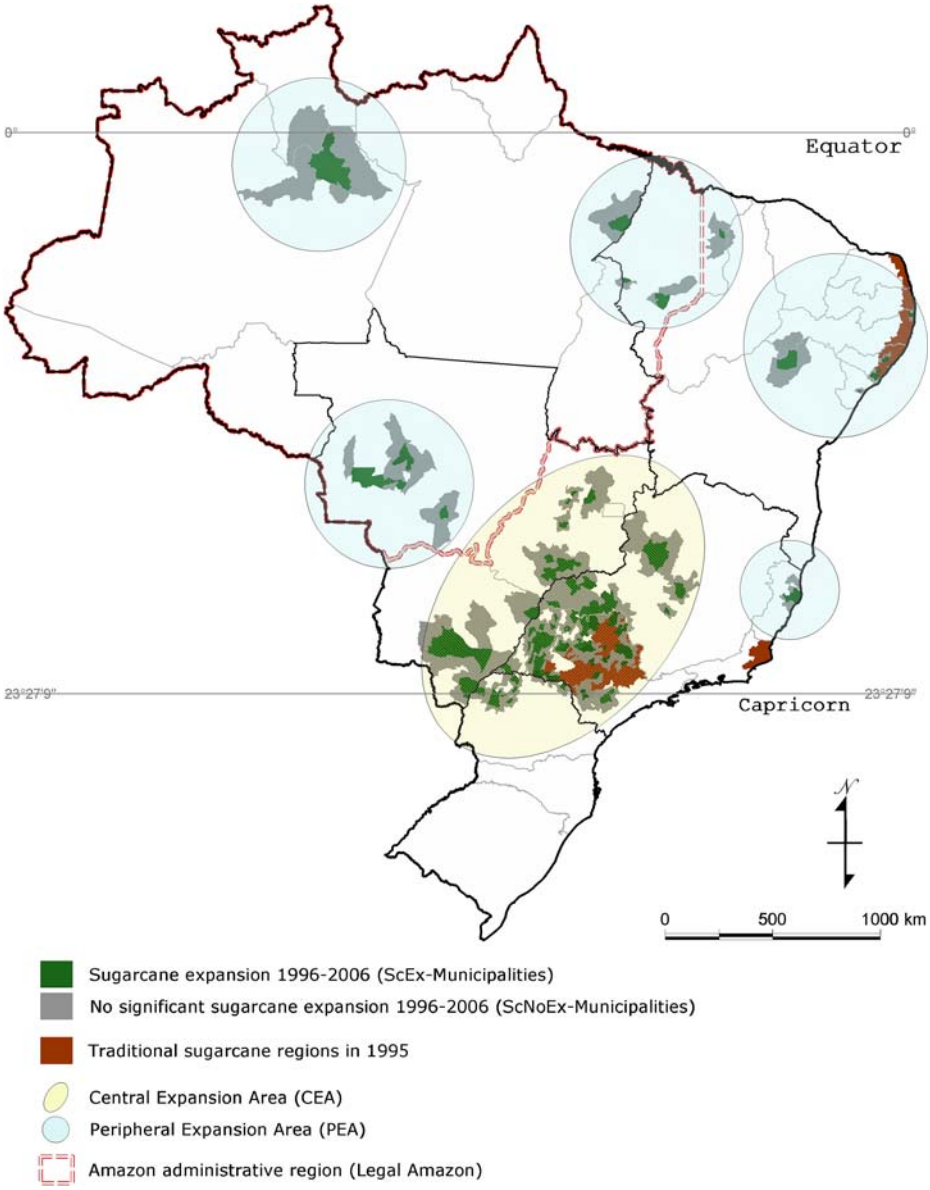

Fig. 2 The geographical distribution of **ScEx** and neighboring **ScNoEx** areas in Brazil. Note that the total municipal areas are shown, rather than the part of the municipal areas that is covered by sugarcane plantations. Traditional sugarcane regions are also shown

forests in 2006 were substantially below the minimum legal requirement (80% in the Amazon region) in both **ScEx** and **ScNoEx.** With lower numbers, **PEA-NoAm**, showed the same trend. These results suggest that sugarcane expansion can lead to further direct deforestation in remote and more preserved regions that have already lost a substantial forest area to agricultural expansion.

Table 2 Differences between ScEx and neighboring ScNoEx municipalities in CEA

Variable	Period	Central Expansion Area			Unit
		ScEx	ScNoEx	Signif. (Student)	
Sugarcane in the municipality	2006	24.72	9.1	0.00	% of municipal area
Increase of sugarcane in the municipality	1997–2006	10.9	6.0	0.00	% y^{-1}
Forest area in farm land	2006	10.3	11.1	0.38	% of farm area
Forest area difference in farmland (2006 minus 1996)	1996–2006	2.7	2.1	0.30	%
Other crops area in the municipality	2006	20.0	19.3	0.77	% of municipal area
Other crops increase in the municipality	1997–2006	1.5	2.0	0.57	% y^{-1}
Pasture in farm land	2006	39.0	51.7	0.00	% of farm area
Pasture area difference in farmland (2006 minus 1996)	1996–2006	−12.3	−9.4	0.04	%
Cattle head density in the municipality	2006	53.9	72.5	0.00	head.km^{-2} of municipality
Cattle head increase	1997–2006	−1.6	−0.2	0.00	%.y^{-1}
Municipal Gross Domestic Product (MGDP)	2005	217,767	138,915	0.02	R$.$10^3$ per municipality
MGDP increase	1999–2005	2.0	1.0	0.11	%.y^{-1}

3.2.2 Land use

Displacement of food crops In **CEA**, the cropland areas used for other crops than sugarcane (proxy variable for displacement of food crops by sugarcane expansion) were similar in **ScEx** and **ScNoEx** in 2006, and increased at the same rates during 96–06. Thus, the expansion of sugarcane did not significantly affect food crop production during the studied period. Possible explanations include: (i) improvements of infrastructure stimulated by the sugarcane expansion also stimulated the cultivation of other crops; and (ii) soybean, peanut (Arachis hypogaea) and cover crops are traditionally cultivated in areas where sugarcane is renewed. This area represents 15–20% of the area cultivated with sugarcane, implying that when the sugarcane expands, this cultivation opportunity also increases.

In **PEA-NoAm** the cropland areas used for other crops than sugarcane were lower in **ScEx** than in **ScNoEx**, while no difference between **ScEx** and **ScNoEx** was detected in **PEA-Am**. **PEA-NoAm** includes a region where family agriculture based food production for self consumption and local market supply is dominant. The results for **PEA-NoAm** therefore raise concern about possible impacts on food security.

Extensive land use The main LUC effects detected were related to pasture area and cattle (Bos indicus, Bos taurus) production (proxy variables for extensive land use) which were predominant in both **ScEx** and **ScNoEx**. In **CEA**, the average share of municipal areas under pastures in 2006 was lower in **ScEx** than in **ScNoEx** and also decreased faster during the 96–06 period. Cattle density in 2006 was lower in **ScEx** than in **ScNoEx**, and the number of cattle heads decreased in **ScEx** while it remained stable in **ScNoEx**.

Table 3 Differences between ScEx and neighboring ScNoEx municipalities in PEA

Variable	Period	PEA-Am			PEA-NoAm		
		ScEx	ScNoEx	Signif.	ScEx	ScNoEx	Signif.
Sugarcane in the municipality	2006	6.5	1.4	0.08	27.5	7.9	0.01
Increase of sugarcane in the municipality	1997–2006	13.4	16.3	0.83	6.8	0.2	0.02
Forest area in farm land	2006	30.5	37.5	0.42	10.0	19.9	0.04
Forest area difference in farmland (2006 minus 1996)	1996–2006	−11.5	1.6	0.08	−5.1	2.1	0.19
Other crops area in the municipality	2006	8.9	11.2	0.73	4.2	9.9	0.01
Other crops increase in the municipality	1997–2006	10.8	7.8	0.50	1.5	1.7	0.95
Pasture in farm land	2006	41.7	40.5	0.89	27.6	34.9	0.40
Pasture area difference in farmland (2006 minus 1996)	1996–2006	1.4	1.5	0.99	4.5	1.2	0.61
Cattle head density in the municipality	2006	25.1	25.0	0.99	21.3	25.5	0.63
Cattle head increase	1997–2006	2.5	4.3	0.32	2.1	2.6	0.76
Municipal Gross Domestic Product (MGDP)	2005	164,605	128,879	0.63	279,970	153,512	0.21
MGDP increase	1999–2005	11.9	11.7	0.97	8.7	4.5	0.13

For variable units see Table 2

The results support the thesis that sugarcane primarily competes with pastures. Sugarcane expansion obviously leads to discontinued cattle production on pastures where the plantations become established. The discontinued cattle production can induce either (i) increased intensity in already established cattle production elsewhere; or (ii) conversion of additional land to pastures (i.e., indirect LUC). The methods adopted for this study did not allow for determining the extent by which sugarcane expansion caused displacement of cattle production to other regions. However, the fact that no increase in cattle heads was detected in **ScNoEx** indicates that the migration of cattle production, if it occurred at significant rates, was long distance and reaching beyond the neighboring municipalities. The migration may have followed a traditional pattern of establishment in remote regions at the border of the Amazon. In this case, indirect CO_2 emissions related to possible deforestation may have occurred.

PEA did not show the same differences between **ScEx** and **ScNoEx** in relation to the extensive land use proxy variables. Cattle density was substantially lower in **PEA**, but in contrast to **CEA** the number of cattle heads increased in both **ScEx** and **ScNoEx** during 96–06, indicating that **PEA** regions have experienced a substantial increase in cattle production during the period. At municipal level sugarcane expansion did not affect extensive land use in **PEA**. A probable explanation is that the municipalities in this region cover substantially larger areas.

Local economy In **CEA**, Municipal Gross Domestic Product (MGDP, proxy variable for local economy) in 2006 was greater in **ScEx** than in **ScNoEx** and also increased faster during 1996–2006, possibly indicating that sugarcane expansion induces economic

development and diversification involving not only increased cultivation but also local industrialization. Differences between **ScEx** and **ScNoEx** were not found for **PEA-Am** and were less evident in **PEA-NoAm**.

4 Overall conclusions and discussion

In **CEA,** sugarcane expansion during the period 1996–2006 resulted in a significant reduction of pastures and cattle heads and higher economic growth than in neighboring areas not experiencing significant sugarcane expansion. Sugarcane expansion in Brazil did not in general contribute to direct deforestation in **CEA**, were most of the expansion took place. In this traditional agricultural region, the amount of forests on farmland was below the minimum stated in law in 1996 and the situation did not change over the period 1996–2006.

The criteria for minimum forest area on private farmland in Brazil were first established by a Federal law in September 15, 1965 (Law # 4771/1965). The required minimum level of forest area on private farmland has been revised upwards several times for different Brazilian regions and is still a topic of discussion in the parliament. But the current values for Central-South part of Brazil (20% of forests) and Amazon (80% of forests) have been stable for a long time. The law also establishes that a land owner having less forests than the minimum required area should plant 1/10 of the minimum requirement every third year until the minimum required area has been reached. As has been reported above, there is a large gap between the requirements in legislation and what is achieved on the average farm today, and there is no established procedure to sue farmers that do not meet the minimum forest area requirement.

Occurring at smaller rates, expansion of sugarcane in **PEA**, containing more preserved regions such as the Amazonian biome and the Northeast region, was related to several negative externalities: direct deforestation, competition with food crops and absence of economic growth. As noted, **PEA** had a small share of total expansion in 1996–2006, and these regions are not expected to become important sugarcane growing areas in a near future. **PEA-Am** is limited because of infrastructure, logistics and distance from market and also more restrictive environmental legislation. The major part of **PEA-NoAm—**Northeast of Brazil—can only expand sugarcane production with irrigation, which is not common practice for sugarcane production in Brazil. Finally, the likely most important reason is that large areas in **CEA** are still available for expansion and can be expected to be the first choice for already established actors planning to expand their operations. However, the more distant future (beyond the coming 10–15 years) is less certain and the establishment of mitigating measures in **PEA** is warranted.

The extent by which sugarcane expansion induces indirect LUC in remote regions could not be established in this study. There is limited knowledge concerning migration and re-establishment patterns among displaced agents. Thus, the linking and quantification of indirect LUC caused by sugarcane expansion in different areas of Brazil is presently not possible to achieve with high confidence due to lack of empirical data. Nevertheless, the possibly large CO_2 emissions that might arise from indirect LUC—as illustrated by, e.g., Fargione et al. (2008)—motivate the development of sugarcane expansion models that reduce the risks of such indirect effects. Expansion models, where sugarcane production is integrated with the previously existing land uses, can potentially promote increased food crop and livestock production and reduce the incidence of migrating extensive cattle production (Sparovek et al. 2007). The results reported in this article indicate that displacement rather than integration occurred during the studied period. Thus, if integration

with prevailing land uses is identified as a preferred model for sugarcane expansion, regulation mechanisms may need to become established that support such developments.

Acknowledgement Financial support from the Swedish Energy Agency and the Brazilian Ministry of Agrarian Development is gratefully acknowledged.

Appendix 1: Additional information about the data analysis

Mean values were calculated and significance of differences were tested following Students test procedures after removal of outliers and inconsistent values that could potentially bias mean and deviation values, or compromise the accuracy of the selection procedure described in the main text. Outliers and inconsistency removal followed a sequence of procedures. First, the selection procedure described in the main text was complemented with validation routines (Eq. 1):

$$
\begin{aligned}
&\text{IF } (Municipality == NoComparableArea)\\
&\quad THEN\ Municipality == NoAnalysed\\
&\quad ELSE\ IF \begin{bmatrix} (M == yes\ AND\ SI >= 2.5\%\ AND\ SR >= 5,000)\ OR \\ (M == no\ AND\ SI >= 5\%\ AND\ SR >= 7,000) \end{bmatrix}\\
&\qquad THEN\ Municipality == ScEx\\
&\qquad ELSE\ IF\ (ScHarv >= 33\%)\\
&\qquad\quad THEN\ Municipality == NoAnalysed\\
&\qquad\quad ELSE\ IF\ (Municipality == Adjacent\ ScEx)\\
&\qquad\qquad THEN\ Municipality == ScNoEx\\
&\qquad\qquad ELSE\ Municipality == NoAnalysed
\end{aligned}
$$

End IF

In this step municipalities with none comparable areas in the period of 1996 to 2006 (NoComparableArea meaning a difference of area >5%), usually because of municipal divisions, were excluded from the analysis. No expansion municipalities with sugarcane representing more than 33% of the municipal area in 2006 were also excluded from the **ScNoEx** group. The rationale is, that if sugarcane is hegemonic, occupying extensive areas of the municipality, no LUCC change effect can be detected because the entire dynamic of the municipality is since long related to sugarcane production. Also, all **ScNoEx** municipalities not adjacent to a **ScEx** were removed, to control for regional differences effects on the variables. These criteria resulted in 143 **ScEx** and 419 **ScNoEx**.

After this steps that applied for all municipalities, additionally pin-point exclusions were made in the cases of:

- State capital municipalities
- Immediate neighboring municipalities to state capitals and metropolitan regions
- MGDP extremely higher than the regional mean MGDP

These criteria were necessary to remove municipalities with predominant urban, metropolitan and regional center dynamics, which contrast with the rural character of most municipalities of **ScEx** and **ScNoEx,** and could thus bias the values of several variables. The application of these criteria resulted in 136 **ScEx** and 407 **ScNoEx**, (keeping 93% and 97% of the original **ScEx** and **ScNoEx** groups remaining after the above described validation routines (Eq 1).

After removal of municipalities each set of variables were checked for inconsistent values, which were individually removed from the analysis, by attributing a null value. For the census data we eliminated municipal records in which the area of pasture or forests exceeded the recorded area of total farmland (Eq. 2):

$$IF\ [(AreaPasture/AreaFarmald) > 1\ OR\ (AreaForest/AreaFarmald) > 1]$$
$$THEN\ Variable\ Record\ ==\ Null$$

End IF

For the yearly estimates of crops based on PAM a similar procedure was adopted, but in this case, the crop area could not exceed the municipal area (Eq 3):

$$IF\ (AreaCrop/AreaMunicipality)\ >\ 1$$
$$THEN\ Variable\ Record\ ==\ Null$$

End IF

The aim of these procedures was to exclude from the census and PAM database records with inconsistent values considering the obvious impossibility of true values for Eq 2 and Eq 3. Of 6,516 possible values in the database, if all values for all variables were false for Eq 2 and Eq 3, 97 were excluded (true values fro Eq 2 and Eq 3), representing an exclusion of 1.5% of the variables.

The variables mean values presented for **CEA** and **PEA** were not meaningfully affected by the outliers and inconsistency eliminations, but the probabilities of the means test were reduced. Data elimination was not only effective to exclude areas that *a priori* were not comparable, but also produced a data universe with less internal variance (as indicated by the improvement in the probability of mean differences), even considering the exclusion of only a small amount of values.

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