Centre for Climate Change Economics and Policy

Grantham Research Institute on Climate Change and the Environment

Dynamics of indirect land-use change: empirical evidence from Brazil

Saraly Andrade de Sá, Charles Palmer and Salvatore Di Falco

March 2012

Centre for Climate Change Economics and Policy Working Paper No. 86

Grantham Research Institute on Climate Change and the Environment

Working Paper No. 74

The Grantham Foundation for the Protection of the Environment

E·S·R·C Economic & Social Research Council

University of Leeds

LSE The London School of Economics and Political Science

Dynamics of Indirect Land-Use Change: Empirical Evidence from Brazil

by

Saraly Andrade de Sá
PEPE-ETH, Professorship of Environmental Policy and Economics, ETH Zurich
E-mail address: *saraly.andrade@env.ethz.ch*

Charles Palmer
Department of Geography and Environment, London School of Economics

and

Salvatore di Falco
Department of Economics, University of Geneva

⋆ The authors would like to thank participants at the London School of Economics 2011 Workshop on Land-Use Changes and Deforestation, the UQAM Economics Department 2012 Seminar, and at the 2012 EAERE conference in Prague, as well as Michele Baggio, Julien Daubanes, Stefanie Engel, Mehdi Farsi, José Féres, Steve Gibbons, Ben Groom, Renger Herman van Nieuwkoop, Pierre Lasserre, Eustáquio Reis, Diana Weinhold and two anonymous referees. Financial support from the North-South Center at ETH Zurich is gratefully acknowledged. Finally, we thank Elizabeth Barona for providing some of the maps used in the paper. The usual disclaimer applies.

Abstract

The expansion of a given land use may affect deforestation directly if forests are cleared to free land for this use, or indirectly, via the displacement of other land-use activities from non-forest areas towards the forest frontier. Unlike direct land conversion, indirect land-use changes affecting deforestation are not immediately observable. They require the linking of changes occurring in different regions. This paper empirically estimates these indirect effects for the case of Brazil. It presents evidence of a positive relationship between sugarcane expansion in the south of the country and cattle ranching in the Amazon, suggesting that the former is indeed displacing the latter towards the forest frontier. This displacement effect is shown to be a dynamic process materializing over 10 to 15 years.

Keywords: Indirect land-use changes; Dynamic effects; Biofuels; Deforestation

1. Introduction

In many tropical countries, agriculture often competes with standing forests for land. Hence, deforestation drivers can be generally understood as factors that increase the rents associated with agricultural expansion. Such factors include increased agricultural output prices, better agro-ecological conditions, lower input prices, better roads and infrastructure as well as technological progress (see, for example, Kaimowitz and Angelsen, 1998; Angelsen and Kaimowitz, 1999; Barbier and Burgess, 2001). The role and the impact of these drivers have commonly been analyzed at the forest frontier, i.e. in regions where forest conversion to agriculture is observed. However, expanding agriculture may also cause indirect land-use changes. These occur when agricultural activities displaced from one region drive expansion of the same land use in another region (Searchinger *et al.*, 2008; Barona *et al.*, 2010; Lapola *et al.*, 2010; Arima *et al.*, 2011). Indeed, diverting land from say pasture for cattle ranching to the production of sugarcane may result in supply shortfalls of the former. Holding demand constant, these supply shortfalls may in turn provide farmers with incentives to create new pastures elsewhere, for example in forest areas.

In this paper, we empirically assess the possible indirect effects of sugarcane expansion in the central and southern regions of Brazil, in particular in the state of São Paulo, on forest conversion decisions in the country's Amazon region. Further, we examine the evidence for a mechanism through which these effects might materialize, namely a displacement of cattle ranching activities from São Paulo state to the Amazon.

Andrade de Sá *et al.* (2012) derive the formal conditions under which such a displacement effect may occur. They show that a necessary condition for displacement is that the output of the displaced activity faces a relatively inelastic demand, which might be the case, for instance, if the displaced crop is a staple food produced and consumed locally, or if the country is a major producer and exporter such that its supply affects international prices. This effect applies to the expansion of any land use including agricultural commodities that could be used either for the production of food or biofuels (see Gallagher, 2008). Focusing on the expansion of the area of land under sugarcane in Brazil for the production of ethanol, we join the debate about the desirability of biofuels as oil substitutes. From the perspective of biofuels providing carbon savings vis-à-vis fossil fuels (e.g. Feng *et al.,* 2010; Righelato and Spracklen, 2007), any potential impact on deforestation will clearly reduce their attractiveness. The reduction in greenhouse gas emissions from oil substitution may be, at least partially, off-set by the decrease in carbon stocks resulting from induced forest conversion.

In Brazil, increased ethanol production resulted in a significant expansion of the amount of land allocated to sugarcane. From 1975 to 2008, the latter increased from 1.9 to 8.9 million hectares such that currently, "sugarcane and its derivatives are the second main primary power source of the national energy matrix, and the domestic ethanol consumption is already superior to the one of gasoline" (MAPA, 2009). Nevertheless, there are growing concerns about the possibility of sugarcane expansion provoking indirect land-use changes leading to deforestation in the Amazon. For example, the World Bank (2011) notes that about two-thirds of the area into which sugarcane expanded came from converting pasture land with the remainder coming from substituting other crops (32%) and from converting natural vegetation (2%). Yet, despite rapid gains in productivity in both sugarcane and pastures, which reduced the indirect effects of agricultural land expansion, "the resulting higher price of land has probably put pressure on pasture expansion further north to the Cerrado and the Amazon biome" (World Bank, 2011: 19).

This paper joins an emerging body of research on indirect land-use change in Brazil. Nassar *et al.*'s (2008) descriptive statistics for the period 2005-2008 suggest very low indirect land-use changes associated with sugarcane expansion, with 0.08 hectares of deforested land for each additional sugarcane hectare. More recently, de Souza Ferreira Filho and Horridge (2011) investigate the same issue but using a computable general equilibrium model calibrated with Brazilian data from 2005. According to their simulations over the period 2008-2020, "each extra sugarcane hectare [will be] associated with 0.14 hectares fall in unused [mainly naturally forested] land and with 0.47 hectares fall in pasture", which is higher than the estimates from Nassar *et al.* (2008). Utilizing a suite of models, Lapola *et al.* (2010) also simulate possible indirect land-use changes resulting from the expansion of both sugarcane ethanol and soybean biodiesel in Brazil and estimate the potential carbon balance. They find that such changes are likely to off-set the carbon savings from biofuels.

None of these studies, however, provided any empirical evidence if and, if so how, expanding land allocated to sugarcane production might influence land-use change, specifically deforestation in the Amazon. Indirect land-use effects are assumed to materialize in all three studies via the displacement of cattle production to the forest frontier driven by the expansion of land allocated to sugarcane production elsewhere. Two recent papers by Barona *et al.* (2010) and Arima *et al.* (2011) are among the first attempts, to our knowledge, to establish empirical evidence for the possibility that land-use displacement in one area might be driving land-use change in another. Note, however, that unlike our paper, neither focuses on the potential indirect land-use effects of expanding land allocated to sugarcane production.

Barona *et al.* (2010) use Geographic Information System (GIS) methods and municipality-level statistics on land use across the Legal Amazon, between 2000 and 2006, to examine the spatial patterns and statistical relationships between deforestation and changes in pasture and soybean areas. Consistent with previous research, their results show that deforestation is predominantly a result of expanding pasture. They also offer limited support for the hypothesis that an increase in land allocated to soy in Mato Grosso has displaced pasture further north, leading to deforestation elsewhere. Yet, they were unable to establish causal links between land-use change in one place (in this case, soy replacing pasture) and change in another (pasture replacing forest). The spatial displacement of causality implies clear difficulties for the measurement of indirect land-use changes (see Babcock, 2009). Arima *et al.* (2011) present a spatial regression model, which attempts to overcome this constraint. By incorporating spatial weights matrices, their model links the conversion of forest to pasture, to land-use change elsewhere in the Legal Amazon. They link deforestation specifically to the expansion of soy production in a settled agricultural area via a land "cascade" from the latter to the forest frontier. Deforestation between 2003 and 2008 is thus shown to be strongly related to soy expansion elsewhere. The largest indirect land-use effect is observed with the inclusion of a lagged soy variable to account for the possibility that displacement to frontier areas may take some time to occur. The effect is found to be "amplified in magnitude beyond a one-to-one replacement of new for old pastures" (p.3).

These studies on indirect land-use change naturally relate to the literature on deforestation drivers, although our analysis more explicitly considers such drivers. Pfaff (1999), Chomitz and Thomas (2003), and Andersen *et al.* (2002) highlight the role played by roads and credit facilities, among other factors as key drivers of deforestation in the Brazilian Amazon. Yet the studies by Barona *et al.* (2010) and Arima *et al.* (2011) share a key insight from some of the older literature on deforestation drivers, which is that forest conversion and land-use changes are phenomena that exhibit spatial patterns. Not only does forest conversion tend to concentrate around particular areas, such as roads and rivers, for instance, but there is also evidence that forest areas located close to conversion regions are under higher pressure (Pfaff, 1999; Chomitz and Thomas, 2003; Andersen *et al.*, 2002). In a similar vein, certain agro-ecological conditions, infrastructure and zoning rules may result in a concentration of crops in some regions.[1] This result has led to a general increase in the use of spatial methods that can control for spatial auto-correlation in forest conversion decisions.

[1]For instance, Brazil's national agronomy institute, EMBRAPA, has developed agro-ecological zones for different crops. These help determine the most productive regions (see www.embrapa.br). For sugarcane, this zoning has resulted in the banning of production in the Legal Amazon (EMBRAPA, 2009).

Spatial methods such as those used by Arima *et al.* (2011) are appropriate for the analysis of neighboring/contiguity effects (see also Anselin, 2009). However, they are not suitable for exploring possible links between the expansion of sugarcane in the south of Brazil with forest conversion in the Amazon. The former is situated thousands of kilometers from the latter (see Figure A.1 in Appendix A). The displacement of any agricultural activity due to the expansion of sugarcane could take a number of different forms, which are not observable in spatial data. Using spatial methods would require assuming a determined structure of displacement, which, if incorrect may lead to misleading results. Cattle displacement from the south of Brazil to the Amazon could have occurred in different ways. For example, there is evidence that from the 1970s onwards, numerous small- and medium-scale farmers sold their land in the south of Brazil and migrated to the Legal Amazon in order to take advantage of an abundance of cheaper land there (e.g. Schneider, 1992; Arima and Uhl, 1997; Margulis, 2004). In particular, cattle farmers in São Paulo state were observed to sell their land to sugarcane growers before migrating to the Amazon. Some migrated gradually over time while others moved more-or-less immediately to the forest frontier. In addition to farmers establishing new properties at the frontier, cattle farmers already operational in the Amazon may have increased the size of their herds, e.g. via purchases of cattle from the south, in response to supply shortfalls in São Paulo.

Historically, São Paulo state is where the majority of Brazilian sugarcane has been produced. We investigate the evidence for a possible mechanism linking sugarcane expansion in São Paulo and deforestation in the Amazon, that of cattle displacement from the former. Yet, the destination of displaced cattle cannot be shown. Given the difficulties of observing spatial causality in the data, causal links can only be shown first between head of cattle and deforestation in the Amazon and second, between sugarcane expansion and head of cattle in São Paulo state. Since a direct causal relationship cannot be established between sugarcane expansion in one area and deforestation in another, an indirect empirical link is established via changes in cattle herd size at the forest frontier.

To assess indirect land-use effects on deforestation due to sugarcane expansion, we apply the Arellano-Bover (1995)/Blundell-Bond (1998) System-GMM estimator to a panel dataset of Brazilian land uses, along with a number of other variables, spanning a 36-year period from 1970 to 2006. In dealing with potential endogeneity among the explanatory variables, this estimator ensures that efficient parameters' estimates are obtained. Additionally, it supports the use of lagged values of the explanatory variables, which allows us to investigate the dynamic effects on forest conversion in the Amazon. Lagged interaction terms are utilized in order to separate out the direct effects of cattle ranching on deforestation from the indirect land-use effects of cattle ranching due to sugarcane expansion in the state of São Paulo.[2]

Our results suggest a positive relationship between sugarcane expansion in São Paulo state and deforestation in the Amazon from 1970 to 2006. The impact of cattle ranching on forest conversion is found to be sensitive to the amount of land allocated to sugarcane in São Paulo state. This result holds even after controlling for other factors that drive deforestation. An indirect land-use effect is evidenced through the long-run marginal effects of cattle on deforestation, which suggest that a 10- to 15-year period was necessary for it to materialize. Although this result is suggestive of a displacement effect, it does not show whether cattle was displaced by sugarcane production in the first instance. To further probe this, two different reduced-form regressions are presented, both of which use the same dataset along with a fixed-effects panel estimator. We first find that increased areas of land allocated to sugarcane production in São Paulo is associated with a decline in cattle herd size in that state over the 1970-2006 period. Second, deforestation in the Amazon may be partially explained by numbers of head of cattle, which in turn are found to be positively correlated with past numbers of head of cattle in São Paulo.

[2]Interaction terms were utilized, for similar purposes, by Lewis *et al.* (2009) to analyze the effects of open-space conservation policies on lakeshore development in Wisconsin. In considering the components that drive both the direct and indirect effects of zoning, for example, they interact zoning (lake-specific characteristic) with the amount of frontage on a parcel (parcel-specific characteristic).

2. Background

This section presents background information on the development and current status of the Brazilian ethanol market and on deforestation in the Brazilian Amazon. Our analysis is motivated by Brazil for a number of reasons. First, Brazil is currently the second largest global ethanol producer (MAPA, 2009), with large-scale production occurring for more than 20 years. This provides us with a sufficiently long time frame for investigating the dynamics of indirect land-use changes. Second, it hosts the largest part of the Amazon rainforest, which has registered relatively high levels of deforestation in the past. Relatively good, long-term data on land use are available for Brazil unlike many tropical forest countries. Additionally, Brazil is also a major global producer of several other agricultural commodities, in particular soybean and beef (World Bank, 2011). This is an important feature as it translates into many activities potentially being displaced by the expansion of sugarcane production. Finally, the main sugarcane production area is located far from the Amazon forest frontier. Since the notion of indirect land-use changes presupposes that the expanding land use is displacing other activities towards a different region, Brazil is an ideal laboratory for examining the possibility of these in the empirical record.

2.1 The Brazilian ethanol market

Ethanol production in Brazil began in the late 1970s with the beginning of the *PróAlcool* program. The aim of the program was to lower the country's dependence on imported oil via public intervention. To stimulate production, *PróAlcool* was used to distribute subsidies to expand sugarcane production, construct distilleries and conduct public research on, for example, new sugarcane varieties. On the demand side, the government opted for fuel blending mandates, e.g. E85, which created domestic demand for ethanol. Although never officially terminated, the program's subsidies were gradually withdrawn from 1998 onward and, to date, none remain. This period was nevertheless sufficiently long to develop a large, national ethanol market.

The new market resulted in the area under sugarcane increasing from 1.9 to 8.9 million hectares from 1975 to 2008. Associated production rose from around 89 to 589 million tons (MAPA, 2010).[3] Most of this expansion, in both ethanol and sugarcane production, occurred in the central and southern region of Brazil, in particular São Paulo state. Approximately 70% of Brazilian sugarcane is currently produced in that state alone (UNICA, 2009).[4] Ethanol production increased from about 0.6 million cubic meters in 1975, to 27.5 million cubic meters in 2009.[5]

As reported by the World Bank (2011), almost all of the expansion of area under sugarcane in Brazil occurred on land that was already under agricultural and livestock production. Remote sensing data have been used to highlight spatial patterns in the allocation of Brazilian land use. With Landsat data, for example, Rudorff *et al.* (2010) show the results of direct land-use change in response to sugarcane planted in São Paulo state in 2007. For the entire state, 56.5% of the expanded sugarcane area occurred over pasture land with the remainder over agricultural land planted with annual crops. Scaling up for the entire country, the spatial patterns of pasture and sugarcane production between 1990 and 2006 can be seen in Figure B.1 in Appendix B. In the top set of maps, an increase in sugarcane area can be observed, particularly in São Paulo state and others in the Center-South region. The bottom set of maps indicates a general decline in livestock units in many of the same areas where sugarcane areas have expanded, and increases in areas to the north of São Paulo including the Amazon region. In sum, these maps are suggestive of the displacement of land allocated to cattle ranching as a consequence of the expansion of the area of land under sugarcane.

[3]Sugarcane production can also be measured in terms of Total Reducing Sugar (TRS) which is the final refined product that can be transformed into either sugar or ethanol. During the 2009/2010 season, of the total amount of TRS produced, 57% was devoted to ethanol. In 1975, the ethanol share was only 13%.

[4]Data available at http://www.unica.com.br/dadosCotacao/estatistica/.

[5]1 cubic meter is exactly equivalent to 1000 liters.

These huge increases in land area under sugarcane and ethanol production are both expected to continue apace, driven by national and international demand. In the national market, demand further increased after the introduction of flex-fuel cars, which are able to run with any blend of ethanol and gasoline. In 2008, 1.2 million of these vehicles were produced in the country.[6] Regarding international demand, Brazil began exporting ethanol in 1989, although exports only reached significant amounts after 2004 (MAPA, 2010). By 2009, around 3.3 million cubic meters of Brazilian ethanol were exported (*ibid*). The country expects exports to continue to rise with the decision of many European Union member-countries to introduce their own blending mandates in the coming years (REN, 2009).

2.2 Deforestation in the Brazilian Amazon

Brazil hosts around 60% of the Amazon rainforest. It corresponds to the North region of the country (*Região Norte*) and includes the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins, with an estimated surface area of 3.6 million square kilometers. Note that states are composed of numerous counties (*municípios*), the third tier of government. The Legal Amazon, which is a larger area than the North region, is a geopolitical construct established by public authorities in 1966 for planning purposes (Andersen *et al.*, 2002). Additional to the states mentioned above, it includes parts of Maranhão and Mato Grosso raising the total area to 5.2 million square kilometers, which corresponds to about 60% of Brazilian territory.

In the 1960s, public credit and subsidies to agriculture coupled with road network development fostered migration to the Amazon (Rudel, 2005). Government programs promoting the occupation of the region were mainly thought of as means to develop the area and release demographic pressure from other parts of the country (Pfaff, 1999). The progressive occupation of the Legal Amazon has gradually changed deforestation

[6] Data available at http://www.unica.com.br/dadosCotacao/estatistica/.

patterns with cattle ranching replacing timber exploitation as the main source of rents from forest conversion, from the 1970s onwards (Andersen *et al.*, 2002). Indeed, IBGE data show that the size of the cattle herd in the Legal Amazon has increased from 6.5 million in 1970 to 55.4 million head of cattle by 2006. Annual forest loss in the Legal Amazon remained relatively stable at around 20,000 square kilometers in the 1970s and 1980s before ranging from 10,000 to 30,000 square kilometers during the 1990s. Table C.1 in Appendix C presents annual forest loss in the previous decade.[7] Despite a sharp decline from the beginning to the end of the decade, forest loss in 2010 at approximately 6,450 square kilometers is comparable to observed amounts of deforestation in Indonesia (FAO, 2010). Much of this forest loss occurred in the states of Rondônia, Mato Grosso and Pará along the southern and eastern edges of the Amazon, the so-called "arc of deforestation" (Alves, 2002; Rudel, 2005).

3. The conceptual framework

We begin by following Pfaff's (1999) land-use model which allows for many possible determinants of deforestation. The underlying theory behind this model is that farmers allocate land between alternative uses in order to maximize their returns. For simplicity, it is assumed that farmers at the forest frontier choose between two land uses $l = \{c, u\}$, where c denotes cleared land put under agricultural production and u denotes uncleared land (i.e. where forests are kept standing). Therefore, at time t, a plot of land j within county i is allocated to one of the alternative uses so as to maximize profit:

$$\max \Pi^l_{ijt} = P^l_{ijt} Q^l_{ijt}(I^l_{ijt}) - W^l_{ijt} I^l_{ijt}, \tag{1}$$

where P^l_{ijt} are the plot level prices for the vector of alternative outputs from any given land use, Q^l_{ijt} is the vector of outputs, I^l_{ijt} is the vector of inputs used, and W^l_{ijt} are

[7] Data from INPE – Brazilian National Institute of Spatial Research – available at http://www.obt.inpe.br/prodes/prodes_1988_2010.htm. Values for 2010 are estimates.

plot-level prices for the vector of inputs.

The P_{ijt} and W_{ijt} plot-level output and input prices may not be observable in practice. These prices result from the realization of equilibria in broader markets, which are jointly determined by both local and non-local (e.g. regional, national, international) conditions. Therefore, we can consider P_{ijt} and W_{ijt} to be functions not only of local but also of non-local parameters. For instance, output prices may depend on local, national and international demand shifters such as population and transport costs. For the same reasons, input prices at the plot level depend not only on local market equilibria but also on the demand for these inputs in other regions. Therefore, we depart from Pfaff (1999)[8] by considering

$$P_{ijt} = P_{ijt}(X_{it}, Z_{kt}) \tag{2}$$

and

$$W_{ijt} = W_{ijt}(X_{it}, Z_{kt}), \tag{3}$$

where X_{it} is a vector of parameters defining local conditions at the forest frontier, i.e. in the $i = \{1, ..., n\}$ forest counties, (e.g. road infrastructure, soil fertility, population, credit received by producers) while Z_{kt} is a vector of parameters corresponding to the $k = \{n + 1, ..., n + m\}$ counties that are not part of the standing forest area. This distinction of counties into forest and non-forest regions will serve our goal of testing whether land-use changes in non-forest regions may affect incentives to clear forest in the Amazon.

Assuming privately optimal input decisions under either land-use $l = \{c, u\}$, (1) yields $I^{l*}_{ijt} = \arg\max \Pi^l_{ijt} = I^{l*}_{ijt}(P^l_{ijt}, W^l_{ijt})$. Combining this with (2) and (3), we define a value function $V^l_{ijt} \equiv \Pi^{l*}_{ijt} \equiv V^l_{ijt}(X_{it}, Z_{kt})$. Thus, normalizing a plot area to unity, total

[8] As is traditional in the literature on deforestation drivers, Pfaff (1999) only considers local parameters and parameters in neighboring counties.

forest conversion in a given county i, at a given time t is

$$y_{it} = \Sigma_j \mathbb{1}_{\{V^c_{ijt} > V^u_{ijt}\}}, \tag{4}$$

where $\mathbb{1}_{\{V^c_{ijt} > V^u_{ijt}\}}$ is an indicator function.

Up to this point, we have assumed a static framework to render clear the role that changing conditions in non-forest areas play in determining forest conversion decisions. However, in practice, deforestation is a dynamic process in which changes to key factors occurring in previous periods are likely to have affected current conditions and, therefore, current decisions. For instance, areas that were previously partially cleared may be easier to access and deforest today. In the same vein, public policies such as subsidized credit lines or colonization programs may take a few years to impact deforestation. To account for these, we introduce lagged values of our parameters in the estimation. Thus, from (4) we derive the following linearized expression to be estimated:

$$y_{it} = \hat{y}_{it} + \epsilon_{it}, \tag{5}$$

where

$$\hat{y}_{it} = \beta_0 + \beta_1 y_{i,t-s} + \beta_2 X_{i,t} + \beta_3 Z_{k,t} + \beta_4 Z_{k,t-s} + \beta_5 X_{i,t} Z_{k,t} + \beta_6 X_{i,t} Z_{k,t-s} + \mu_i, \tag{6}$$

is the estimated amount of forest conversion at time t in county i, $s \geq 1$ is the number of lags and μ_i are county-specific unobservable fixed effects.

Obtaining consistent parameter estimates of (5) and (6) is challenging for two reasons. First, we consider our dependent variable to be dynamic in the sense that it depends on past realizations. Second, a number of the explanatory variables in X_{it} and Z_{kt} are unlikely to be strictly exogenous. Taken together, these suggest that obtaining consistent parameter estimates necessitates the use of a generalized method of moments

(GMM) dynamic estimator. More precisely, we use the Arellano-Bover (1995)/Blundell-Bond (1998) System-GMM estimator, which implies a transformation of the regressors, usually by taking differences, and the use of the lagged values of the dependent variable as instruments as well as initial conditions in the levels of the regressors.

At this point, one may ask why a simultaneous equations approach, i.e. jointly estimating the whole system of output supply and demand for inputs in forest areas, is not employed. We acknowledge that this approach is also valid. However, several reasons led us not to opt for it. First, since equation (4) is defined as a sum of indicator functions, the cross properties arising in a conventional supply/demand system would have been lost through the imposition of restrictions on the parameters of equation (6). Therefore, the simultaneous equations approach would not have enhanced the estimation's results. Moreover, as stated earlier, we focus here on the dynamic aspect of indirect land-use change. Doing so using a simultaneous equations approach would have been less tractable than the one adopted in our analysis.

4. Data sources and description of variables

For our empirical analysis we constructed a panel data set using secondary data for all of Brazil's counties for the years 1970, 1975, 1980, 1985, 1995-96 and 2006. Since the structure of counties has changed during this time span, we aggregated the municipal data into 3,652 Minimum Comparable Areas[9] (MCAs), 258 of which are within the Legal Amazon. These constitute our units of observation, i, for our investigation of the drivers of deforestation in the Amazon (Section 5.1). São Paulo state comprises 567 MCAs, which constitute our units of observation for exploring the relationship between sugarcane area and cattle herd size in those MCAs (Section 5.2).

While the Brazilian National Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística*, IBGE) datasets are the only reliable source of information

[9] The list of Brazilian MCAs from 1970 to 2005 was provided by the Brazilian Institute of Applied Economic Research (*Instituto de Pesquisa Econômica Aplicada*, IPEA).

available for our purposes, they present some limitations. First, there may be a lack of precision with regards to the estimates of deforestation in cases where producers failed to make a direct declaration. This resulted in estimates having to be obtained indirectly from statements regarding land use in the various agricultural/cattle ranching properties. Also, the IBGE Census, in principle, includes all these properties in the Legal Amazon but fails to give information relating to publicly owned or unclaimed land. Deforestation, therefore, may be underestimated (Margulis, 2004). Additionally, the level of aggregation (MCA) may have led to less precise estimates of variables such as the distance to the state capital and road density. Finally, the gaps between censuses (five to ten years) can also lead to a loss of important dynamic information.

Tables D.1 and E.1 (see Appendices D and E), respectively, present a description of the main variables used in the analysis and offer some descriptive statistics.

4.1 Land use and land cover

Land-use data were obtained from IBGE's agricultural censuses undertaken in 1970, 1975, 1980, 1985, 1995-1996[10] and 2006. They include data on total land cleared, extent of natural pasture and head of cattle. "Total land cleared" is defined by IBGE as the sum of land under perennial crops, annual crops, planted pasture, planted forests as well as long and short fallow land.[11] Our dataset contains similar land-use data for all

[10]For the 1996 census, IBGE changed the reference as well as the data collection period. Data were collected in August 1996 instead of January as in previous censuses. Thus, officially, these data are not strictly comparable to those collected both in the previous and following censuses. Some scholars have argued that the apparent decrease in production and rural employment in 1996, when compared to the 1985 census, may have been due to this change in the data collection period. Since August corresponds to the end of the agricultural season in Brazil, most precarious establishments – i.e. temporary farms occupied by squatters, sharecroppers and land tenants that are only active during the agricultural season – may not have been properly identified (Helfand and Brunstein, 1999, cited in Andersen *et al*, 2002). However, some macroeconomic changes during the period 1985-1996, including the elimination of most agricultural subsidies in the late 1980s, may also partly explain these results (Andersen *et al.*, 2002). Additionally, as long as the eventual undercount can be assumed to be randomly distributed among municipalities, it should not affect our econometric analysis (*ibid*). Following this line of reasoning, we opted to include the 1996 data in our analysis.

[11]These data were used instead of satellite measures of deforestation for two main reasons. First, satellite data, such as those supplied by the Brazilian National Institute of Space Research (INPE, *Instituto Nacional de Pesquisas Espaciais*), cover fewer points in time before 1988 compared to the

counties in Brazil, both including those in the Legal Amazon and in the state of São Paulo. For investigating evidence of indirect land-use effects on deforestation due to the expansion of land allocated to sugarcane production, we consider the number of hectares allocated to sugarcane in São Paulo state. As previously noted, this state accounts for the majority of Brazilian sugarcane and ethanol production.

4.2 Socioeconomic data

Data on the counties' GDP, population and rural credit[12] were obtained through IPEA.[13] We used data on counties' resident populations to compute GDP per capita and population density variables for our units of observation. Regarding roads, we were only able to obtain state level data using the *Anuários Estatísticos do Brasil*, which were provided by IBGE. We used the total values, which included municipal, state and federal roads, both paved and unpaved. To obtain average MCA values we multiplied the state-level total kilometers of roads by the proportion of each MCA area relative to the state area.

4.3 Geo-ecological data

Climate and soil characteristics have been shown to play a role in forest conversion. For instance, according to Chomitz and Thomas (2003) regions with higher rainfall are less appropriate for agriculture and thus less prone to forest conversion. We therefore include average annual precipitation for each MCA. Finally, we obtained data on average soil fertility of each municipality through shapefiles made available by IBGE. The fertility

survey data, e.g. data from INPE were only available for 1978, 1988, and annually thereafter. The survey data, by constrast, were collected at reasonably regular intervals when the Brazilian censuses took place. Second, IBGE data reflect net deforestation (i.e. gross deforestation minus secondary regrowth) while satellite data reflect gross deforestation (Anderson *et al.*, 2002). Nevertheless, as noted earlier, we acknowledge that survey data may be more vulnerable to biases due to misreporting on the ground. See Anderson *et al.* (2002) for a discussion of the different types of land cover data and how they compare.

[12] In our regressions we used "average credit received by farmers of a given MCA" as a control variable. This variable was computed by dividing, for each year, the total value of rural credit allocated in the MCA by the number of rural properties in that same MCA.

[13] Available at www.ipeadata.gov.br.

categories used are: very low (1); low (2); medium (3); medium-high (4); and, high (5) soil fertility. We adopted IBGE's classification when aggregating information to the MCA level (by computing the average fertility value for all municipalities within a given MCA).

5. Empirical results

In this section, we investigate how land allocated to sugarcane in the state of São Paulo could be indirectly influencing patterns of deforestation in the Amazon, by adopting a twofold strategy.

First, in subsection 5.1, we test for the existence of an indirect link between sugarcane expansion in São Paulo state and forest conversion in the Amazon region. To that end, the dynamic equation presented in (5) and (6) is estimated using the Arellano-Bover (1995)/ Blundell-Bond (1998) System-GMM estimator, and the two-step procedure is applied.[14] Since the latter is known to yield biased standard errors we use the bias-corrected robust variance estimator developed by Windmeijer (2005), known as the WC-robust estimator. This allows us to obtain unbiased standard errors that also allow for heteroskedasticity in the errors.[15] Along with the role played by sugarcane expansion, we also discuss the role of the more traditionally-considered drivers of deforestation, which are included as control variables in the regression analysis.

Second, using a fixed-effects estimator, subsection 5.2 examines further evidence for the displacement of cattle to the Amazon due to the expansion of sugarcane in São Paulo state. We first test the proposition, implicit in the remote sensing data described in Section 2, that sugarcane expansion in São Paulo occurred at the expense of cattle ranching activities before examining links between the size of cattle herds in São Paulo

[14]The regressions were also undertaken using the Difference-GMM estimator of Arellano and Bond (1991). Results were similar but less consistent across specifications. This can be explained by the fact that the System-GMM estimator, by using additional moment conditions, is a more precise estimator and has better finite sample properties (Cameron and Trivedi, 2009).

[15]The system GMM estimator uses lags of the dependent variable as instruments. It is implemented using stata 11 xtdpdsys command (StataCorp., 2009).

and the Amazon.

5.1 Sugarcane expansion in São Paulo and deforestation in the Amazon

The results are reported in Table 1 below. The dependent variable in all specifications is "hectares of cleared land in the Legal Amazon MCAs". We focus on the dynamics of the problem. This recognizes, for instance, that the impact of sugarcane on deforestation may need "time to build" or that current deforestation depends on past deforestation. We thus begin with a simple specification where only head of cattle in the MCAs (cattle), current and lagged values of sugarcane acreage in the state of São Paulo (SPsgcn, L.SPsgcn and L2.SPsgcn) and a lagged-dependent variable are used as regressors (L.cleared) (see models 1 and 2). Additional explanatory variables are then included. In models 3 to 5, we sequentially include interaction terms between current head of cattle in the Legal Amazon MCAs and current and lagged values of sugarcane hectares in São Paulo state (SPsgcnCattle, L.SPsgcnCattle and L2.SPsgcnCattle). We provide the interpretation of the coefficients associated with these interaction terms below. Finally, in models 6 and 7 we include additional control variables, which capture some of the agricultural and socio-economic characteristics of the MCAs.[16]

Head of cattle is treated as endogenous. The estimated coefficient is positive and statistically significant. As expected more cattle ranching in the Amazon is associated with more deforestation. This effect appears to be sensitive to sugarcane expansion (see below). Among the controls, road density (road_dens) is also treated as endogenous.

[16] In the Arellano-Bover/Blundell-Bond approach, the error term ϵ_{it} is assumed to be serially uncorrelated, which implies that there should be no evidence of second-order correlation in $\Delta\epsilon_{it}$. This condition is essential to obtain consistent parameter estimates. Tests for second-order correlation are provided in Table F.2 of Appendix F. The null hypothesis of no serial autocorrelation is not rejected in any of the different specifications used, implying that the assumption of serially uncorrelated ϵ_{it} is supported by the data. An additional condition for the System-GMM estimator to produce consistent estimates is to use valid moment conditions. We can test whether the over-identifying moment conditions are valid by performing the Sargan test of over-identifying conditions, as discussed in Arellano and Bond (1991). However, since we use robust standard errors that deal with potential heteroskedasticity in the data, the Sargan test becomes baseless. We nevertheless perform it on non-robust versions of all the specifications. The null hypothesis of valid over-identifying restrictions is rejected for models 1-5 but not for models 6 and 7.

This is in line with the existing literature. The decision to construct a new road or extend a preexisting one, especially when taken by state and/or municipal authorities, may be responding to local demand in already-cleared areas rather than resulting from exogenous decisions to "conquer" new territories (see Pfaff, 1999 and Andersen *et al.*, 2002). The remaining control variables are hectares of natural pasture (natpast), GDP per capita (gdpcap), population density (pop_dens), average credit granted to farmers (credit), distance to the state capital (dist_state_cap), soil fertility (fertility), precipitation (precip), and area of MCA (area_ha - to control for the relative size of MCA). Moreover, in model 7 we include agricultural GDP in São Paulo (gdpagric_SP) to control for the possibility that the expansion of sugarcane could be proxying for general growth of agriculture in the state. This in turn could also be affecting land-use changes at the forest frontier. Table F.1 in Appendix F presents a correlation matrix for the variables used in these estimations.

Table 1: Estimations' results

	model 1	model 2	model 3	model 4	model 5	model 6	model 7
L.cleared	0.930***	0.983***	0.790***	0.828***	0.752***	0.531***	0.501***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
L2.cleared		-0.158***	-0.113***	-0.105*	0.101	-0.0187	-0.0285
		(0.000)	(0.000)	(0.032)	(0.181)	(0.732)	(0.562)
cattle	0.298***	0.332***	1.211***	1.456***	1.898***	1.641***	1.623***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
SPsgcn	-0.0116	-0.0238	0.0628	0.0867	0.0881*	0.102**	0.127*
	(0.766)	(0.571)	(0.071)	(0.056)	(0.037)	(0.004)	(0.018)
L.SPsgcn	-0.0229	0.00202	-0.157*	-0.187*	-0.137*	-0.170**	-0.174*
	(0.739)	(0.978)	(0.012)	(0.017)	(0.038)	(0.001)	(0.013)
L2.SPsgcn	0.0435	0.0330	0.113**	0.110**	0.0367	0.0502*	
	(0.207)	(0.363)	(0.001)	(0.005)	(0.307)	(0.026)	
SPsgcnCattle			-0.000000237***	-0.00000154*	-0.00000156*	-0.00000116	-0.00000119
			(0.000)	(0.013)	(0.027)	(0.146)	(0.095)
LSPsgcnCattle				0.00000171*	3.83e-08	0.000000353	0.000000486
				(0.036)	(0.967)	(0.711)	(0.598)
L2SPsgcnCattle					0.00000219***	0.00000111*	0.000000993*
					(0.000)	(0.025)	(0.012)
road_dens						29179.4	615996.0
						(0.913)	(0.093)
natpast						0.171*	0.189**
						(0.016)	(0.003)
gdpcap						-1.072	-0.736
						(0.208)	(0.590)
pop_dens						8.927	8.308
						(0.265)	(0.098)
credit						0.0000107***	0.0000122***
						(0.000)	(0.000)
dist_state_cap						44.98	101.1
						(0.881)	(0.674)
area_ha						0.0119	0.0177*
						(0.074)	(0.013)
fertility						-44731.4	-51494.1
						(0.511)	(0.403)
precip							102.1
							(0.085)
gdpagric_SP							-0.00116
							(0.148)
_cons	19015.0	22449.0	-14968.3	-20940.4	-33057.1**	29251.7	-223199.0
	(0.095)	(0.063)	(0.084)	(0.064)	(0.007)	(0.789)	(0.152)
N	1032	1032	1032	1032	1032	942	938
chi2	52927.2	66336.6	62714.3	58363.0	99587.7	57886.1	69920.8

p-values in parentheses

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

5.1.1 The role of sugarcane

To investigate whether sugarcane expansion in the state of São Paulo affects forest conversion decisions in the Amazon we include current and lagged values of sugarcane hectares in the former as regressors, and interact them with the current size of cattle herds in the latter. This should capture the impact of sugarcane expansion on forest conversion that we hypothesize to materialize indirectly through a substitution of ranching activities away from São Paulo to the Amazon.

Looking at the results in Table 1 we first note the statistical significance of the majority of the lagged dependent variables. This suggests that the dynamic model is indeed appropriate. Regarding the coefficients associated with the interaction terms, we observe that these are consistent in terms of their relative size, sign, and degree of significance across specifications.[17] We also note that the estimated coefficient for current sugarcane becomes significant once we include the full set of interactions. The coefficient of the interaction between head of cattle and sugarcane acreage lagged twice (L2.SPsgcnCattle) is positive, significant and stable irrespective of the specification considered. Note, however, that it becomes slightly less significant once the control variables are added in models 6 and 7. In contrast, both coefficients associated with the interaction terms between head of cattle and sugarcane acreage in current period (SPsgcnCattle) and sugarcane area lagged once (L.SPsgcnCattle) are no longer significant once the control variables are added.

Although insignificant, one may speculate what both a negative estimated coefficient of cattle interacted with contemporaneous sugarcane acreage and a large positive coefficient of cattle coefficient might indicate. We thus considered the possibility that, combined with the large positive coefficient on the size of the cattle herd, this negative coefficient might be suggestive of sugarcane expansion in São Paulo drawing capital away

[17]Higher lags of sugarcane acreage were also included in the interaction terms but were not shown to have any significant impact on cleared land.

from forest conversion for cattle. To explore this possibility, we included the value of agricultural investments made by farmers both in the Legal Amazon MCAs as well as in the state of São Paulo, in model 7. These data were also obtained through IPEA and IBGE. The inclusion of agricultural investments has no effect on the sign, relative size or significance of any of the interaction terms compared to the results for models 6 and 7, in Table 1. Hence, the possibility that the expansion of sugarcane attracted capital from the Amazon region is not supported by the data.

In general, the results for the interaction terms imply that the role played by head of cattle in forest conversion is sensitive to the area of sugarcane in the state of São Paulo in previous years. They also suggest that in the absence of land allocated to sugarcane production, cattle ranching would have had a smaller impact on land clearing in the Amazon. The adoption of a dynamic model also allows us to distinguish between the long- and medium/short-run effects of the variable of interest. We thus compute both the long- and medium/short-run marginal effects of cattle on cleared land for models 6 and 7.[18] The magnitude of these effects in both models is similar.

The medium/short-run marginal effect is around three hectares of cleared land per additional unit of livestock. When the long-run effect is added to the medium/short-run effect, the overall, marginal effect increases by about one-third to almost four hectares of cleared land per additional head of cattle. So, the magnitude of deforestation due to cattle is higher once the long-run marginal effects associated with sugarcane production are factored in. These marginal effects may seem high at the first sight. Yet we note that they are consistent with the more extensive ranching methods in the Brazilian Amazon compared to those observed in São Paulo state since 1970 (See Table G.1 in Appendix G).

Extensive practices have long been a feature of forest frontier expansion in the Ama-

[18] Assuming a model of the kind $y_t = \alpha_1 y_{t-1} + \alpha_2 y_{t-2} + \beta_1 X_t + \beta_2 X_{t-1} + \delta_1 X_t Z_t + \delta_2 X_t Z_{t-1} + u_t$, the marginal long-run effect of X on y is given by $(\beta_1 + \beta_2 + \delta_1 \overline{Z} + \delta_2 \overline{Z})/(1 - \alpha_1 - \alpha_2)$, where $\overline{Z}$ is the mean of Z across all observations and all years. Similarly, the short-run marginal effect of X on y is given by $(\beta_1)/(1 - \alpha_1 - \alpha_2)$.

zon, mainly due to the abundance of cheap land (e.g. White *et al.*, 2001 and Rudel, 2005). Pacheco (2012) describes how such practices tend to be practiced by medium- to large-scale, relatively well-capitalized, landholders rather than smallholders farming less than 100 hectares of land. But how might the expansion of sugarcane in São Paulo be linked to the long-run marginal effect of cattle on deforestation in the Amazon? As noted in the introduction, farmers in the Amazon may have responded to supply shortfalls by expanding their herds. Since our results indicate an indirect land-use effect that materialized after 10 to 15 years, we might expect such a response to have occurred within a relatively shorter time frame.

A longer time frame, on the other hand, might be more plausibly explained by the phenomenon of farmers migrating from the south of Brazil to the forest frontier. Since the 1970s, much land previously utilized for cattle ranching in São Paulo state was purchased or taken over by sugarcane growers. Taking advantage of cheaper land in the Legal Amazon, southern cattle farmers either migrated spontaneously or were induced, for example, to participate in government colonization programs. Capital constraints, particularly in the 1980s and early 1990s, may have provided further incentives for farmers to sell their land in São Paulo and invest in the Amazon.[19] Many were able to obtain proportionately more land than they owned in the south (Margulis, 2004). After a number of years, some of the same landowners sold out to better-capitalized landowners, possibly before migrating deeper into the forest (White *et al.*, 2001). Alternatively, farmers may have migrated gradually from areas in the south of Brazil towards the Amazon. Either way, there may have been a substitution of cattle ranching activities, from being relatively more intensive (in São Paulo state) to less intensive (in forest frontier areas in the Amazon).[20] Our data, however, do not allow us to further explore

[19]We thank one of the anonymous reviewers for this insight (see also, Margulis, 2004).

[20]Note that larger, better-capitalized landowners may undertake more intensive cattle ranching activities instead of extensive ones (Margulis, 2004). This is, however, more likely to occur where land is less scarce, i.e. away from the forest frontier, in the more consolidated areas within the "arc of deforestation". Indeed, state-level data from IBGE suggest that cattle stocking densities increase the further one moves away from the frontier.

these different explanations for the indirect land-use effect.

In summary, the results for the coefficients associated with the interaction terms in Table 1 are suggestive of an indirect effect of sugarcane expansion in São Paulo on deforestation in the Legal Amazon MCAs. The overall, marginal effect comprises both short- and long-run effects of cattle on deforestation in the Amazon. Through the interaction terms, the latter can be interpreted as an indirect effect of (past) sugarcane expansion on (current) deforestation. Such a delayed effect is consistent with the gradual substitution of cattle ranching away from the main sugarcane production areas in the south of Brazil to the Amazon frontier. Note, however, that the coefficients associated with the interaction terms are only suggestive about such a mechanism. More precisely, they identify an indirect land-use effect on deforestation as a consequence of sugarcane expansion, one that appears to materialize through cattle herd size at the forest frontier.

5.1.2 The traditional deforestation drivers

We include in the regression analysis factors that have been identified in the literature as key drivers of deforestation in the Brazilian Amazon. These are hectares allocated to natural pasture, road density, average amount of credit allocated to farmers, soil fertility, population density, precipitation, GDP per capita and distance to state capital (which can be interpreted as a proxy for access to markets). In our analysis these variables serve the purpose of control variables. In general, all of these factors are expected to exhibit a positive relationship with cleared land except for distance to state capital, which is expected to have a negative relationship with cleared land. As shown in Table 1, whenever significant, the coefficients associated with these regressors present the expected sign and are therefore in line with previous studies (e.g. Pfaff, 1999 and Andersen *et al.*, 2002).

5.2 Additional evidence for displacement

In the previous subsection, we concentrated on documenting the impact of sugarcane expansion in São Paulo state on deforestation in the Legal Amazon. But precisely how cattle has been displaced, thus affecting changes in size of cattle herds at the frontier, is not a question we can address with our dataset. Yet, irrespective of how displaced cattle materialize at the frontier, they would need to be displaced in the first instance, i.e. by a different land use. This possibility has, to some extent, been documented in the remote sensing data described in Section 2.1. They suggest a displacement in land use across Brazil over time. As the amount of land under sugarcane production expanded in the south of Brazil, the numbers of livestock in those same areas appeared to decline. At the same time, livestock numbers in the northern areas of the Center-South region along with areas of the Amazon appeared to rise.

To complement the findings of the remote sensing analyses and further probe the displacement hypothesis, we investigate whether similar patterns emerge in our dataset using two different approaches. A reduced form fixed-effects model associated with robust standard errors is adopted in both instances.

We first restrict our investigation to the possibility of a correlation between cattle herd size and sugarcane area in São Paulo state, between 1970 and 2006. A more comprehensive empirical model of the determinants of cattle herd size in the south is thus left for future work. "Number of head of cattle in São Paulo state's MCAs" is the dependent variable. From Table H.1 in Appendix H, the coefficient associated with sugarcane area is negative and highly significant. In model A, head of cattle declines by 0.324 for each additional hectare of sugarcane. Hence, land allocated to sugarcane production in a given MCA is negatively correlated with the number of head of cattle in the same area.

Second, we implement two additional regressions to see if there is any evidence of a correlation between the size of cattle herds in the Legal Amazon and in São Paulo state. Specifically, we test whether the portion of the increase in numbers of head of cattle in the Amazon that is correlated with lagged values of numbers of head of cattle in São Paulo is also associated with increased deforestation.[21] We first run a fixed-effects regression between current numbers of cattle in the the Legal Amazon MCA against lagged numbers of cattle in São Paulo. The fitted values are retained before being used as an explanatory variable in a second regression where deforestation is explained by these. Results, reported in Appendix H, show that there is a positive and statistically significant correlation between current numbers of cattle in the Amazon region and lagged numbers of cattle in São Paulo. This positive correlation suggests that the more cattle there were in São Paulo in the previous 10 to 20 years, the more prone these were to displacement by the expansion of sugarcane. Moreover, the fitted values are positively and significantly correlated with land clearing in the Amazon. We therefore find statistical evidence that deforestation in Amazon may be partially explained by numbers of cattle in the Amazon, which in turn are correlated with past numbers of cattle in São Paulo.

Together the results from these different approaches are consistent with the remote sensing evidence of a displacement of activities from the South to the North. They provide additional empirical support to the hypothesis that sugarcane expansion in São Paulo state displaced cattle ranching activities to other regions, including the Amazon.

6. Discussion and Conclusions

In this paper, we investigated indirect land-use changes induced by sugarcane expansion in Brazil. First, we found an indirect land-use effect of sugarcane expansion on deforestation, which is sensitive to the number of head of cattle in the Amazon. This is shown to be a long-run effect, which can be disentangled from the short-run, more direct effect of cattle ranching on deforestation. Although relatively small compared to the effect of

[21] We thank one of the anonymous reviewers for suggesting this strategy.

the traditional deforestation drivers, the indirect effect imputable to displacement is not negligible and statistically significant. Second, land area under sugarcane is shown to be negatively correlated with cattle herd size in São Paulo state. Also, deforestation in the Amazon may be explained by numbers of cattle in the Amazon that are in turn significantly, positively correlated with past numbers cattle in São Paulo. In sum, our results provide empirical support to the hypothesis that that there has been a substitution of cattle ranching activities from the Center-South region towards the Amazon, as a result of sugarcane expansion. This spatial substitution, which we interpret as displacement, has contributed to the increase in cattle herd size in the Legal Amazon since 1970. We therefore argue that this is a channel through which sugarcane expansion during the 1970-2006 period influenced deforestation in the Brazilian Amazon.

The indirect land-use effect is shown to be dynamic with 10 to 15 years passing before it fully materializes. This relatively long time interval suggests that cattle ranching activities have shifted gradually between non-forest and forest regions. But how have such activities shifted across regions over time? From secondary sources, one plausible explanation concerns the documented movements of farmers and ranchers from sugarcane-growing areas to forest frontier areas in the Amazon (e.g. Schneider, 1992; Arima and Uhl, 1997 and Margulis, 2004). However, we neither know the identity nor observe the precise movements of such agents in our dataset. This limits further inference. Future work could collect detailed data describing precisely the origin and previous occupations of cattle ranchers in the Amazon along with the origin of cattle found at the forest frontier. More generally, it is not possible with our data to establish spatial causality between sugarcane expansion in the state of São Paulo and deforestation in the Amazon. Yet, our study is the first to provide empirical evidence that such a relationship between these two land uses might exist.

Since sugarcane is used as an energy crop for ethanol production in Brazil, our results contribute to the debate on the desirability of ethanol as an oil substitute. Under the assumption of no land-use change in supplying the biofuel feedstock, Gallagher (2008) demonstrates that the best greenhouse gas savings from ethanol, compared to gasoline, can be achieved from sugarcane produced in Brazil.[22] But as shown by Lapola *et al.* (2010), these savings begin to dissipate once the indirect effect on forest conversion is taken into account. We note, however, that their results are based on assumed and not observed parameter values. Given the abundance of land in Brazil, the effect calibrated by Lapola *et al.* (2010) may not be as severe as has been assumed. In other words, the displacement effect may have been overstated, at least for cattle displaced by the expansion of land under sugarcane production. While the estimation of the carbon balance of ethanol production in Brazil is beyond the scope of the present paper, our results suggest some possible directions for the design of future policies to promote biofuels.

The expansion of land under sugarcane in São Paulo at the expense of cattle ranching implies that the former could be mandated to be grown on idle land rather than land currently utilized by high-value agricultural commodities. In addition, investments in research aiming at increasing sugarcane productivity could be encouraged. The Brazilian Agriculture Research Corporation (EMBRAPA) in fact continues to undertake work in this direction. Another approach is to integrate cattle and sugarcane cultivation, one that has recently been piloted by Conservation International in São Paulo state (Conservation International, 2010). So far, it has not been shown to be profitable for a number of reasons including competition with other agricultural sectors for land and inputs.

Our results also have policy implications for areas in which the indirect land-use effect eventually materialized. It appears to be associated with more extensive cattle ranching at the forest frontier compared to ranching in São Paulo state where the effect originated. This suggests a role for the application of intensive technologies in the former. White *et*

[22]Note that this result depends on sugarcane yields and whether or not bagasse is utilized for heat and power (Gallagher, 2008).

al. (2001) found, however, that forest scarcity is likely to be a prerequisite for technology intensification. This, of course, is unlikely to be the case at the forest frontier. Strong incentives might be necessary to induce the adoption of new technologies. At the same time, policies could be considered that make deforestation and extensive land uses less attractive for farmers. Policies that attempt to price the positive externalities of the Amazon forest, for example, along with the strengthening of property rights could help make deforestation more costly (see below).

The Brazilian government has plans to further expand its sugarcane/ethanol sector, in part to meet a projected rise in international demand for ethanol. However, the growing body of evidence for indirect land-use changes, in particular those that may induce higher levels of deforestation, challenge the received wisdom about the environmental benefits of ethanol production. Brazil is also fully engaged in putting into place various mechanisms that aim at reducing emissions from deforestation and forest degradation (REDD). Thus, future work could address the broader policy implications of indirect land-use change. For example, incentive payments that effectively price the carbon benefits of forests might make it less attractive for farmers to clear land. Thus, REDD could mitigate against indirect land-use effects, which may need to be taken into account in REDD baseline calculations. The results presented in this paper are a first step in accurately estimating the potential size of these effects.

With respect to policy, two final remarks are in order. First, with less cattle ranching concentrated in São Paulo today in comparison to the past, there may be fewer opportunities for displacement in the future. Second, given the 10-15 year period for displacement to materialize, the long-term monitoring of policy impacts would be necessary.

References

Alves, D. (2002) ”An Analysis of the Geographical Patterns of Deforestation in the Brazilian Amazon in the Period 1991-1996” in C. Wood and R.Porro (eds.) *Deforestation and Land Use in the Amazon*, University Press Florida, Gainsville, Fla.

Andersen, L.E., C.W.J. Granger, E. Reis, D. Weinhold and S. Wunder (2002) *The Dynamics of Deforestation and Economic Growth in the Brazilian Amazon*, Cambridge University Press

Andrade de Sá, S., C. Palmer and S. Engel (2012) “Ethanol, Food and Forests” *Environmental and Resource Economics* 51: 1-21

Angelsen, A. (2007) “Forest Cover Change in Space and Time: Combining the von Thünen and Forest Transition Theories” World Bank Working Paper Series, Washington D.C.

Angelsen, A. and D. Kaimowitz (1999) “Rethinking the Causes of Deforestation: Lessons from Economic Models” *World Bank Research Observer* 14: 73-98

Anselin, L. (2009) “Thirty Years of Spatial Econometrics” *Papers in Regional Science* 89: 3-25

Arellano, M. and S. Bond (1991) “Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations” *Review of Economic Studies* 58: 277-297

Arellano, M. and O. Bover (1995) “Another Look at the Instrumental Variable Estimation of Error-Components Models” *Journal of Econometrics* 68: 29-51

Arima, E.Y. and C. Uhl (1997) ”Ranching in the Brazilian Amazon in a National Context: Economics, Policy, and Practice” *Society and Natural Resources* 10: 433-451.

Arima, E.Y., P. Richards, R. Walker and M.M. Caldas (2011) “Statistical Confirmation of Indirect Land Use Change in the Amazon” *Environmental Research Letters* 6: 1-7.

Babcock, B. (2009) ”Measuring Unmeasurable Land-Use Changes From Biofuels” *Iowa Ag Review* 15: 4-5.

Barbier, E.B. and J.C. Burgess (2001) “The Economics of Tropical Deforestation” *Journal of Economic Surveys* 15: 413-421

Barona, E., N. Ramankutty, G. Hyman and O.T. Coomes (2010) “The Role of Pasture and Soybean in Deforestation of the Brazilian Amazon” *Environmental Research Letters* 5: 024002

Barona, E. (2009) "Identifying the Role of Crop Production in Land Cover Change in Brazil, 1990-2006" mimeo, McGill University

Blundell, R. and S. Bond (1998) "Initial Conditions and Moment Restrictions in Dynamic Panel Models" *Journal of Econometrics* 87: 115-143

Cameron, A.C. and P.K. Trivedi (2009) *Microeconometrics using Stata* Stata Press, College Station, Texas

Chomitz, K.M. and T.S. Thomas (2003) "Determinants of Land Use in Amazonia: A Fine-Scale Analysis" *American Journal of Agricultural Economics* 85: 1016-1028

Conservation International (2010) "Identification of Responsible Cultivation Areas in São Paulo, Brazil. Pilot Test Focusing on Sugarcane and Cattle Integration", Conservation International, downloaded from www.conservation.org (20th June, 2012).

EMBRAPA - Brazilian Agriculture Research Corportation (2009) "Zoneamento Agroecológico da Cana-de-açucar", Rio de Janeiro

FAO - Food and Agriculture Organization of the United Nations (2010) "Global Forest Resources Assessment" FAO Forestry Paper 163, Rome

Feng, H., O.D. Rubin and B.A. Babcock (2010) "Greenhouse Gas Impacts of Ethanol from Iowa corn: Life Cycle Assessment versus System Wide Approach" *Biomass and Bioenergy* 34: 912-921

Gallagher, E. (2008) *The Gallagher Review of the Indirect Effects of Biofuel Production*, Renewable Fuels Agency, London.

Goldemberg, J. (2008) "The Brazilian Biofuel Industry" *Biotechnology for Biofuels* 1: 6

Goldemberg, J. and P. Guardabassi (2009) "Are Biofuels a Feasible Option?" *Energy Policy* 37: 10-14

Kaimowitz, D. and A. Angelsen (1998) *Economic Models of Tropical Deforestation: A Review*, CIFOR-Indonesia

Lapola, D.M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking and J. A. Priess (2010) "Indirect Land-Use Changes Can Overcome Carbon Savings from Biofuels in Brazil" *Proceedings of the National Academy of Sciences* 107: 3388-3393.

Lewis, D.J., B. Provencher and V. Butsic (2009) "The Dynamic Effects of Open-Space Conservation Policies on Residential Development Density" *Journal of Environmental Economics and Management* 57: 239-252.

MAPA - Ministry of Agriculture, Livestock and Food Supply (2009) "Anuário Estatistico da AgroEnergia", Brasilia

MAPA - Ministry of Agriculture, Livestock and Food Supply (2010) "Anuário Estatistico da AgroEnergia", Brasilia

Margulis, S. (2004) "Causes of Deforestation of the Brazilian Amazon" World Bank Working Paper Series, Washington D.C.

Nassar, A.M., B.F.T, Ruddorf, L.B. Antoniazzi, D. Alves de Aguiar, M.R.P. Bacchi and M. Adami (2008) "Prospects of the Sugarcane Expansion in Brazil: Impacts on Direct and Indirect Land Use Changes" in Zuurbier, P. and J. van de Vooren (Eds.) *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment*, Wageningen Academic Publishers

Pacheco, P. (2012) "Actor and Frontier Types in the Brazilian Amazon: Assessing Interactions and Outcomes Associated with Frontier Expansion" Geoforum, doi:10.1016/j.geoforum.2012.02.003

Pfaff, A. (1999) "What Drives Deforestation in the Brazilian Amazon? Evidence from Satellite and Socioeconomic Data" *Journal of Environmental Economics and Management* 37(1): 26–43.

Righelato, R. and D.V. Spracklen (2007) "Carbon Mitigation by Biofuels or by Saving and Restoring Forests?" *Science* 317: 902

Rudel, T.K. (2005) *Tropical Forests: Regional Paths of Destruction and Regeneration in the Late Twentieth Century*, Columbia University Press, New York.

Rudorff, B.F.T., D.A. de Aguiar, W.F. da Silva, L.M. Sugawara, M. Adami and M. A. Moreira (2010) "Studies on the Rapid Expansion of Sugarcane for Ethanol Production in São Paulo State (Brazil) Using Landsat Data" *Remote Sensing*2: 1057-1076.

Schneider, R. (1992) "Brazil: An Analysis of Environmental Problems in the Amazon" Report No. 9104 BR, Vol. 1, The World Bank, Washington D.C.

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T. Yu (2008) "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Changes" *Science* 319: 1238-1240

de Souza Ferreira Filho, J.B. and M. Horridge (2011) "Ethanol Expansion and Land Use Change in Brazil" Center of Policy Studies Working Paper No. G-218

StataCorp (2009) *Stata Statistical Software: Release 11.* College Station, TX: StataCorp LP.

Tilman, D., R. Socolow, J.A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville and R. Williams (2009) "Beneficial Biofuels – The Food, Energy and Environment Trilemma" *Science* 325: 270-271

Weinhold, D. and E. Reis (2008) "Transportation Costs and the Spatial Distribution of Land Use in the Brazilian Amazon" *Global Environmental Change* 18: 54–68

White, D., F. Holmann, S. Fuijsaka, K. Reategui and C. Lascano (2001) "Will Intensifying Pasture Management in Latin America Protect Forests? - Or is it the Other Way Round?" in Angelsen, A. and D. Kaimowitz (eds) *Agricultural Technologies and Tropical Deforestation* CAB International, Oxford

Windmeijer, F. (2005) "A Finite Sample Correction for the Variance of Linear Efficient Two-Step GMM Estimators" *Journal of Econometrics* 126: 25-51

World Bank (2011) *Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits?* World Bank, Washington DC.

Zuurbier, P. and J. van de Vooren (Eds) (2008) *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment*, Wageningen Academic Publishers

Appendices

A Main sugarcane production areas in Brazil

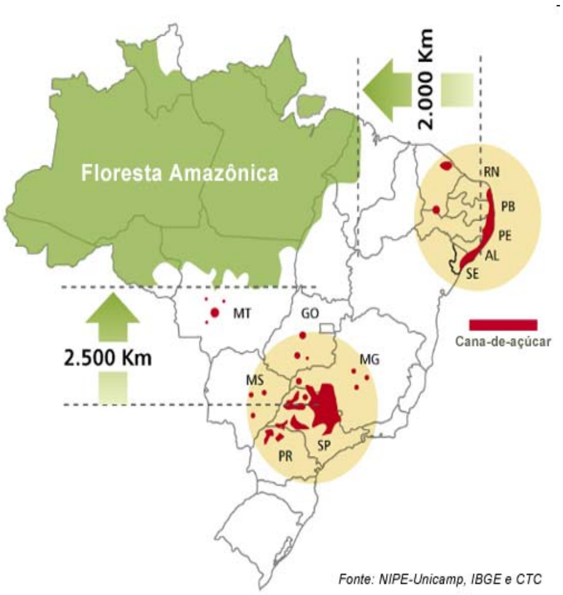

Figure A.1: Main sugarcane production areas in Brazil

B Mapping of main cattle and sugarcane production areas in Brazil

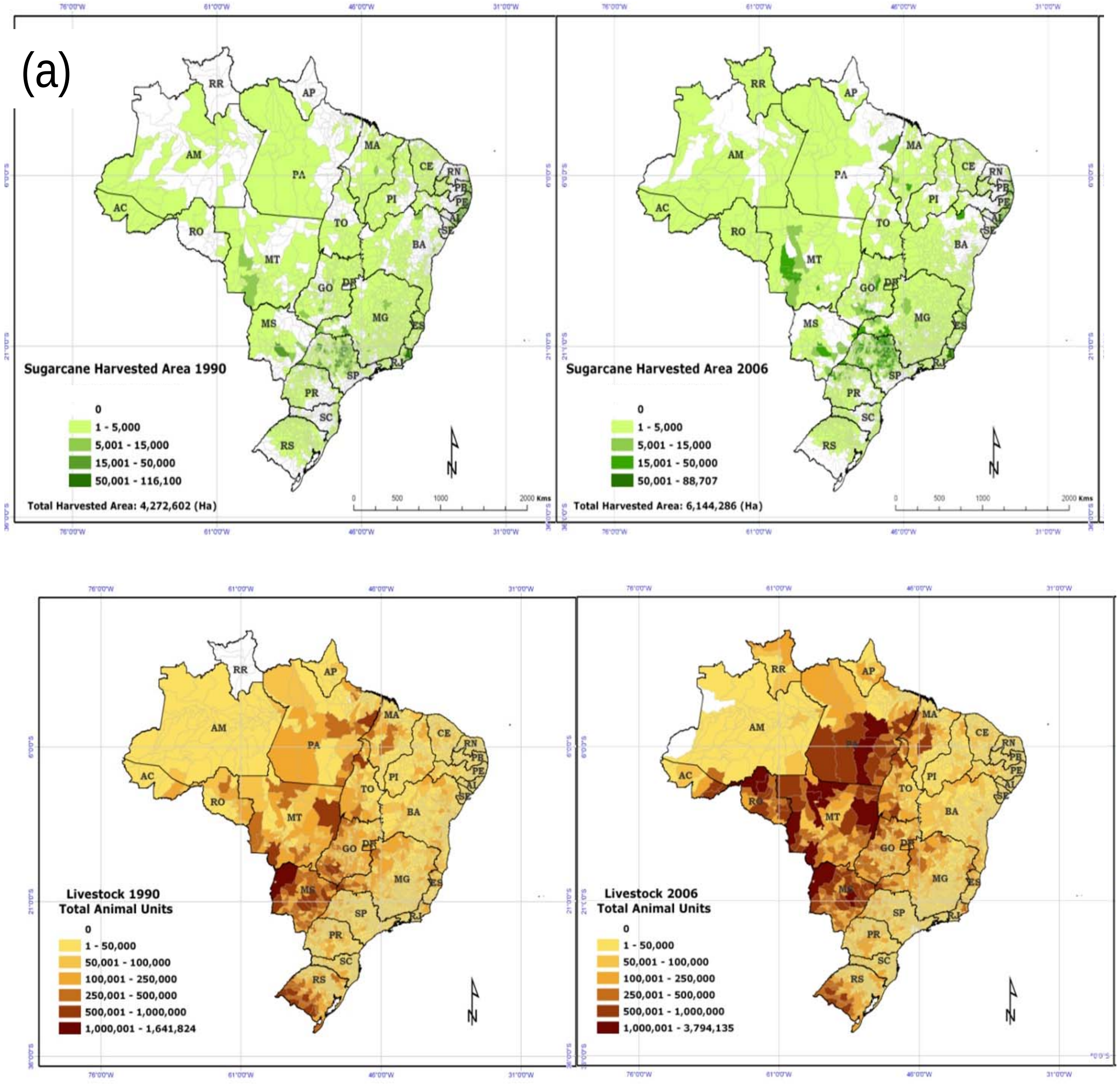

Figure B.1: Spatial distribution of sugarcane and livestock in Brazil (1990-2006). Source: Barona (2009).

C Deforestation in the Legal Amazon

Table C.1: Deforestation in Legal Amazon States(square kilometers, 2000-2010)

States/Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Acre	547	419	883	1078	728	592	398	184	254	167	273
Amazonas	612	634	885	1558	1232	775	788	610	604	405	474
Amapá		7	0	25	46	33	30	39	100	70	0
Maranhão	1065	958	1085	993	755	922	674	631	1271	828	679
Mato Grosso	6369	7703	7892	10405	11814	7145	4333	2678	3258	1049	828
Pará	6671	5237	7510	7145	8870	5899	5659	5526	5607	4281	3710
Rondônia	2465	2673	3099	3597	3858	3244	2049	1611	1136	482	427
Roraima	253	345	84	439	311	133	231	309	574	121	0
Tocantins	244	189	212	156	158	271	124	63	107	61	60
Legal Amazon	**18226**	**18165**	**21651**	**25396**	**27772**	**19014**	**14286**	**11651**	**12911**	**7464**	**6451**

D Variables description

Table D.1: Main variables description

Variable	Definition	Source
cleared	Hectares of land cleared	IBGE - Agricultural Census
cattle	Number of head of cattle	IBGE - Agricultural Census
SPsgcn	Hectares of land under sugarcane in São Paulo state	IBGE - Agricultural Census
natpast	Hectares of natural pasture	IBGE - Agricultural Census
gdpcap	GDP per capita (R$ of 2000)	IPEAdata
pop_dens	Population density (Total MCA population/MCA area)	IPEAdata
road_dens	Road density (km of road within MCA/MCA area)	IPEAdata
credit	Average credit allocated to rural establishments (R$ of 2000)	IPEAdata
area_ha	MCA surface in hectares	IPEAdata
dist_state_cap	Average distance from counties' capital (within a given MCA) to the state capital in km	IPEAdata
gdpagric_SP	Value added of agricultural activities in São Paulo (R$ of 2000)	IPEAdata
fertility	Categorial variable. 1=very low, 2=low, 3=medium, 4=medium/high, 5=high	GIS data from IBGE
precip	Average yearly precipitations in milliliters	IPEAdata

E Descriptive statistics

Table E.1: Descriptive statistics of main variables

variable	mean	max	min	sd
cleared	39957.71	9286486	0	159668.8
cattle	34178.45	8016933	0	138857.3
SPsgcn	1671501	3498240	524139	1051666
natpast	27596.94	4594066	0	118775.4
gdpcap	3485.831	823211.5	0	10832.85
pop_dens	98.32099	201954.5	0	1468.494
road_dens	0.463128	1.309967	0.0012848	0.23718
credit	1.01E+10	4.72E+12	0	7.60E+10
dist_state_cap	249.1717	1476	0	150.8784
area_ha	233225.4	3.67E+07	0	1431832
fertility	1.97E+00	5.00E+00	1	0.9433757
precip	1332.686	3389	346	423.875
gdpagric_SP	1.10E+07	1.72E+07	6439376	3584624

F Correlations and Tests

Table F.1: Correlation matrix among variables

	cleared	L.cleared	L2.cleared	cattle	SPsgcn	L.SPsgcn	L2.SPsgcn	SPsgcnCattle	LSPsgcnCattle	L2SPsgcnCattle	natpast	gdpcap	pop_dens	credit	road_dens	dist_state_cap	area_ha	fertility	precip	gdpagric_SP
cleared	1.000																			
L.cleared	0.953	1.000																		
L2.cleared	0.867	0.933	1.000																	
cattle	0.899	0.836	0.737	1.000																
SPsgcn	0.069	0.094	0.132	0.132	1.000															
L.SPsgcn	0.069	0.093	0.133	0.133	0.999	1.000														
L2.Spsgcn	0.068	0.089	0.129	0.133	0.988	0.991	1.000													
SPsgcnCattle	0.836	0.788	0.694	0.983	0.168	0.169	0.172	1.000												
LSPsgcnCattle	0.830	0.782	0.689	0.981	0.171	0.172	0.175	1.000	1.000											
L2SPsgcnCattle	0.820	0.773	0.679	0.975	0.171	0.172	0.177	0.999	0.999	1.000										
natpast	0.668	0.642	0.564	0.439	-0.026	-0.026	-0.029	0.327	0.317	0.308	1.000									
gdpcap	0.143	0.142	0.134	0.119	0.050	0.046	0.054	0.112	0.111	0.111	0.119	1.000								
pop_dens	-0.050	-0.049	-0.048	-0.042	0.027	0.026	0.028	-0.036	-0.035	-0.035	-0.044	0.027	1.000							
credit	0.642	0.684	0.691	0.519	0.132	0.134	0.145	0.520	0.520	0.521	0.433	0.273	-0.008	1.000						
road_dens	-0.058	-0.036	-0.013	-0.058	0.063	0.063	0.063	-0.048	-0.047	-0.047	-0.067	-0.182	0.019	-0.039	1.000					
dist_state_cap	0.002	-0.006	-0.016	-0.005	-0.024	-0.025	-0.024	-0.003	-0.003	-0.003	-0.001	-0.023	-0.073	-0.012	-0.260	1.000				
area_ha	0.536	0.480	0.426	0.472	-0.012	-0.013	-0.012	0.421	0.416	0.411	0.378	0.204	-0.080	0.225	-0.308	0.136	1.000			
fertility	0.027	0.003	-0.020	0.066	-0.023	-0.023	-0.023	0.066	0.066	0.065	-0.035	0.005	-0.056	-0.049	-0.401	0.138	0.127	1.000		
precip	-0.101	-0.116	-0.125	-0.078	-0.056	-0.057	-0.054	-0.067	-0.066	-0.065	-0.084	0.023	0.121	-0.080	-0.746	0.231	0.122	0.235	1.000	
gdpagric_SP	-0.034	-0.026	-0.065	-0.082	-0.485	-0.519	-0.613	-0.113	-0.116	-0.122	0.030	-0.022	-0.016	-0.133	-0.032	0.013	0.006	0.012	0.028	1.000

Table F.2: Second-order auto-correlation test

	model 1	model 2	model 3	model 4	model 5	model 6	model 7
Arellano-Bond test of second-order auto-correlation	z=1.111 (p=0.266)	z=1.264 (p=0.206)	z=-0.915 (p=0.360)	z=-0.846 (p=0.398)	z=-0.916 (p=0.359)	z=0.923 (p=0.356)	z=0.923 (p=0.356)

G Cattle stocking density in different regions of Brazil

Table G.1: Cattle density (Head of cattle/ha)

Region	1970	1975	1980	1985	1996	2006
São Paulo	1.00	1.00	1.15	1.13	1.41	1.85
Legal Amazon	0.27	0.31	0.39	0.44	0.74	1.04
Cerrado	0.44	0.56	0.62	0.69	0.83	0.96

H Additional regressions

Table H.1: Fixed effects model; dependent variable: Head of cattle in São Paulo municipalities

	model A	
sgcn	-0.324***	
	(0.000)	
_cons	20521.3***	
	(0.000)	
N	3402	
chi2		
p-values in parentheses		
* $p < 0.05$	** $p < 0.01$	*** $p < 0.001$

Table H.2: Fixed effects model; dependent variable: Head of cattle (current) in the Legal Amazon municipalities

	model B	
L.SPcattle	0.149***	
	(0.001)	
L2.SPcattle	0.282***	
	(0.000)	
_cons	-4905984.7***	
	(0.001)	
N	1032	
chi2		
p-values in parentheses		
* $p < 0.05$	** $p < 0.01$	*** $p < 0.001$

Table H.3: Fixed effects model; dependent variable: Hectares of cleared land in the Legal Amazon municipalities

	model C	
fitted_cattle	0.533**	
	(0.004)	
_cons	87087.2***	
	(0.000)	
N	1032	
chi2		
p-values in parentheses		
* $p < 0.05$	** $p < 0.01$	*** $p < 0.001$