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The Conservation versus Production Trade-off: Does Livestock Intensification Increase Deforestation? The Case of the Brazilian Amazon

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Summary

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Keywords: Amazon, Rebound Effect, Intensification, Deforestation, Land Use, Cattle Ranching
JEL Classification: Q53, Q150

This paper has benefitted from comments and suggestions by Diana Weinhold and Henrique Neder, to whom I am greatly thankful. Any errors remain mine. Funding for this research has been provided by the CAPES foundation, Brazilian Ministry of Education.

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The conservation versus production trade-off: does livestock intensification increase deforestation? The case of the Brazilian Amazon[1]

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[November 2014]

Abstract

More cattle, less deforestation? Land use intensification in the Amazon is an unexpected phenomenon. Theories of hollow frontier, speculative behaviour and boom-bust all share the prediction that livestock production will remain largely extensive. Yet between 1996 and 2006 productivity of cattle grew by an astounding 57.5% in the average Amazon municipality. *Does rising land productivity of cattle increase deforestation?* I use secondary data and spatial econometrics to look for evidence of a positive relation between cattle intensification and deforestation ('rebound effect'). The reduced-form model I employ is based on a spatial econometric specification by Arima et al. (2011) and uses panel data at the municipality-level. I show that mounting productivity in consolidated areas has been associated with lower deforestation both in frontier and consolidated municipalities. This suggests that any process of out-migration spurred by the rising productivity is insufficient to have a positive impact on deforestation.

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Introduction

How to feed a population that is growing towards 8 billion while protecting forests and biodiversity? To this question many have pointed land use intensification as the only possible answer, including a recent policy document by political and academic heavy-weights such as Pascal Lamy, Jean-Claude Trichet, Nicholas Stern, Amartya Sen and others (Oxford Martin Commission, 2013). But this optimistic view is disputed by a growing number of scholars. While in principle producing more food in the same area may logically seem to cause demand for land to decrease, in practice, because of second-round effects, the opposite can be the case. With a time lag, using land more intensively in certain areas may positively affect demand for land in forest margins, inducing more deforestation in the long run. The mechanism should be made cleared in the remained of this paper, but it has to do with the change in rents that stems from intensification in consolidated areas and the way it affects migration to the frontier.

A theoretical case can be built for an indirect land use effect of cattle ranching intensification on deforestation in the Brazilian Amazon (Vale and Andrade, 2013). Out-migration of farmers from consolidated areas can be related to changes in land productivity of cattle, with pasture degradation and land markets playing a crucial role in pushing marginalized farmers to move to areas where soils are naturally fertile and average land prices are low. If such process conduces to a sufficiently high level of rural-rural migration, then a characteristic increase in deforestation should be evident in frontier municipalities. Rather, if the land-sparing effect is the predominant force, then deforestation at the frontier should be duly reduced.

In this paper I look for signs of a rebound effect—intensification shooting back and causing more deforestation—at the aggregate, municipality scale. I adopt a new empirical strategy to look at time and space-dynamic effects of land use intensification in the cattle ranching sector, building upon the model by Arima et al. (2011), which tests the hypothesis that expansion of soya in consolidated areas affects deforestation in frontier areas. I use municipality-level census data from a 16-year period in which the livestock sector saw important increases in yields in the Amazon to provide the first empirical assessment of the relationship between productivity growth in consolidated areas and changes in deforestation in frontier locations. I find robust evidence that the increase in productivity was associated with a substantial decrease in deforestation.

The essence of the land-sparing hypothesis is that by being able to increase output by resorting to mostly vertical expansion, farmers in consolidated areas reduce the overall demand for new land in frontier locations. This optimistic idea is sometimes called a 'Bourlaug hypothesis', for the American biologist Norman Bourlaug who is best known as the father of the green revolution. The supposition that increasing yields is the fundamental land-saving mechanism is countered by advocates of the so-called 'Boserup hypothesis'. They state that processes of intensification and extensification are intrinsically related, and while in more densely populated locations productivity of land may be pushed upwards, horizontal expansion into marginal lands is unlikely to cease, as rational farmers unable to cope with the intensification process will look for areas where land abundance allows them to stick to a less labour-intensive production system.

The alternative theory is also referred to as the 'Jevon's paradox' or the 'rebound effect' hypothesis. It states that productivity gains in the use of a natural resource, with initial efficiency gains being overcompensated by second round price and income effects[3]. The classic example is petrol consumption for transportation: all else equal, more efficient automobiles might be expected to save fuel at the aggregate as people would be able to drive the same amount of miles with less petrol. However, as driving a mile becomes less expensive, drivers may automatically adjust to driving more miles, depending on their preference structures. Or else, the lower demand for fuel may push prices down and incomes up, which can eventually feedback on consumption. The resulting net effect could still be a savings, but might well be a more than elastic rise in miles driven, incurring in a negative savings of fuel. The key question is thus how elastic the demand is with respect to prices.

A similar reasoning is often applied to deforestation, as more efficient agricultural and livestock technologies can feedback on demand and overcompensate short term gains (Angelsen and Kaimowitz, 2001; Lambin and Meyfrodt, 2011). For example, Rudel et al.

[3] Gillingham et al. (2013) provide the most up-to-date assessment of the seminal insight by Stanley Jevons in his 1865 book *The Coal Question*.

(2009) compiled data on crop yields and land use across the world and found evidence against the hypothesis of crop productivity gains saving land. Whereas a rebound effect—increased land use following a productivity gain—would require a time lag to operate, the alternative, land-sparing effect—lower land use following a productivity gain—should in principle show up within a shorter time span. Between 1990 and 2005, only in two of nine world regions did land use decrease at the same time as crop yields increased, suggesting that intensification may have indeed backfired on extensive land use.

But the parallel between the Jevon's paradox, which was specifically geared towards energy consumption, and land use change has a major limitation. While the adoption of energy-efficient technologies by consumers is rather straightforward and depends largely on a simple cost/benefit calculation, agricultural technologies are subject to all kinds of adoption biases that lead to below optimal adoption (Duflo et al., 2011) and situations of technological lock-in (Possas et al., 1996). Since technological dissemination is far from granted in agriculture, it is unclear that technology-driven efficiency gains can have the impact necessary for a rebound effect to materialize.

1. Does cattle displacement overcompensate productivity gains?

Cattle livestock plays a pivotal role in global environmental change: it accounted for as much as 18% of anthropogenic greenhouse emissions and 63% of reactive Nitrogen mobilization by the year 2000 (Pelletier and Tyedmers, 2010). Being the key driver of land use change in the Amazon, in recent years different policy initiatives have been implemented in the region with a view to enhance conservation efforts by inducing cattle ranching intensification—thus implicitly assuming the validity of the land-sparing hypothesis[4]. While some authors have found evidence of an indirect land use effect from

[4] See Trivedi et al. (2012) and Strassburg et al. (2012) for the standard land sparing assumption from the point of view of funding parties. Based on those premises a "*low carbon agriculture and avoided deforestation to reduce poverty in Brazil*" programme is being funded by UK Department for Environment, Food and Rural Affairs to incentivize farmers to invest in cattle ranching intensification technologies in various States in Brazil. The Dutch government has also committed funds to a pilot project on sustainable livestock farming to be implemented in the Brazilian Amazon (GTPS, 2012). The Brazilian government has created lines of subsidized credit for a 'low carbon

consolidated to frontier areas in the Amazon for the specific cases of soya (Arima et al., 2011; Brown et al., 2005; Macedo et al., 2012) and sugar-cane (Sa, Palmer and Di Falco, 2012), the land-sparing hypothesis has had minor scrutiny when it comes cattle ranching (as evidenced by Cohn et al., 2011).

A pattern similar to a rebound effect has been observed in some cases within the agricultural sector, both in Latin America and elsewhere (Angelsen and Kaimowitz, 2001; Ceddia et al., 2013). When it comes to cattle in the Brazilian Amazon, however, the evidence is ambiguous. Though a land-sparing effect cannot be ruled out as beef production has grown by 50% from 2004 to 2010 at the same time as deforestation felt by 75% (figure 1), recent evidence put together by Barretto et al. (2013) point to the opposite direction. Looking at the correlation between land use intensity and deforestation at the country scale (with data extracted from satellite pictures), they find that pasture intensification occurs predominantly in consolidated areas in tandem with a broader process of agricultural land use intensification. Moreover, pasture areas decrease in consolidated areas while increasing in frontier areas, with a chronology that resembles an indirect displacement effect associated with the intensification process.

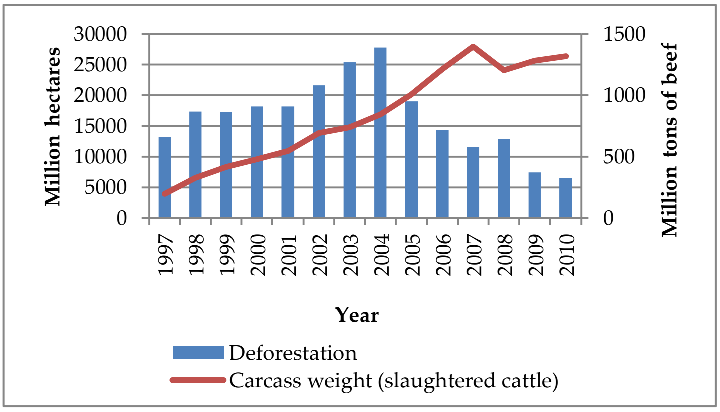

Figure 1. Deforestation and carcass weight of slaughtered cattle in the Brazilian Legal Amazon, 1997-2010.

Sources: National Institute for Space Research (INPE) and Brazilian Geography and Statistics Institute (IBGE)

agriculture programme' that includes recovering degraded pastures; the government's agricultural research and extension agencies have also created their own cattle intensification programmes: Embrapa *Boas Práticas Agropecuárias*, and Emater *Programa Balde Cheio*.

The thin literature that explores causal mechanisms in a multivariate framework has merged livestock with agricultural crops. Using a general equilibrium model, Cattaneo (2002) concluded that in the short term technological intensification in consolidated areas would reduce deforestation, but in the long run, with factor mobility, capital and labour would inevitably migrate to the frontier and cause further clearings, thus increasing deforestation. A potentially complementary conclusion was reached by Marchand (2012), who used cross-sectional census tract data to estimate the technical efficiency of "representative farmers", and found a nonlinear effect of productivity on deforestation. Farmers at the bottom and top of the productivity distribution deforested more than those with intermediary productivity levels. The majority of farmers lay on the ascendant slope, so the combination of higher than average productivity and higher than average deforestation was predominant. These two pieces of evidence reinforce the idea that productivity is not univocally associated with land sparing.

Livestock farming normally occupies marginal lands, with high-yield cropping systems occupying the best soils. The Brazilian Amazon, however, is a hotspot of cattle expansion where livestock competes with other uses, often in good soils (Mann et al., 2014); farmers switch to cattle as soon as they can because it is less labour-intensive and because it provides a form of savings. Cattle expansion in the Amazon used to be mostly horizontal, as there were no constraints to clearing new lands, but the situation has changed over the last two decades[5]:

Table 1. Productivity of cattle ranching (R$ / ha / year), 1996-2006

Region	Municipalities[a]	Δ productivity (96-06)
Pre-frontier	180	41.4%**
Frontier	102	52.7%**
Consolidated	253	70.9%***
Total	535	57.50%

Source: Agricultural Censuses, IBGE.

[a]1,221 municipalities dropped due to missing data.

[5] See Lapola et al. (2014) for a recent empirical assessment of the intensification process.

What happens to deforestation when cattle expands vertically, by intensification? As the literature has quite clearly suggested, it is possible that land is spared, but a chain of indirect causation may spur further deforestation. This would of course not be the case if virtually all farmers would increase production by land use intensification only, while it would definitely be the case if all farmers would keep productivity constant and expand production horizontally. The real world question is what happens when some combination of intensification and traditional ranching is used to increase supply—if vertical and horizontal expansions occur simultaneously, which one dominates?

2. Methods and data

I provide a first test to the hypothesis that land use intensification in consolidated areas pushes low-productivity cattle ranching to the frontier and causes more deforestation. The process I analyse is dynamic both in space and time, so the empirical specification is based on spatially and time-lagged measures of the changes in productivity and deforestation. The model is only estimated over frontier municipalities, with information on key control variables in consolidated areas being captured through a spatial weighting matrix.

I first adapt the reduced form model by Arima et al. (2011) and run a first difference specification of the growth in deforestation (2007 to 2012 as well as other time frames) on the growth in productivity (1996 and 2006). By taking a first difference or a difference from the average on both sides, this model eliminates potential sources of bias coming from omitted variables correlated with the levels of the dependent variable as well as the treatment (table 2 below); variables purposefully left out are those that reflect the very process that links intensification to deforestation, such as migration. The model yields results for cattle that are comparable to Arima et al.'s results for soya: that there is a rebound effect.

Controlling for fixed effects in the levels of deforestation is important inasmuch as the levels of deforestation affect the growth rate of deforestation. However, the key question is how much the *growth* in productivity in consolidated areas affects the *change* in deforestation at the frontier. Intuitively, productivity growth depends on initial levels of productivity: municipalities where productivity is higher to start with should display lower growth rates. The same applies to the other controls and even to the dependent variable itself, so the levels are in principle important additional controls.

Another way of justifying the inclusion of the levels is to see that the deforestation dynamic path is affected by factors other than the levels of deforestation. For instance, institutional characteristics in the different Federal States may *directly* affect the change in deforestation; the initial level of productivity in consolidated areas is in itself a determinant of the migration process (other than the growth in productivity), hence a relevant control in itself; the initial level of deforestation at the frontier may also affect migration, so it is another a relevant control.

To account for the dynamic nature of the cattle indirect land use effect, I improve the model by adding controls that capture fixed effects in growth rates. This procedure has been employed in a similar context by Weinhold and Reis (2008), whom I follow closely in constructing my empirical specification. When this is done, the results from model 1 are reversed. A strong land-sparing effect is now evident, with a series of robustness checks and one placebo test confirming the result. In particular, I find that intensification in consolidated municipalities is associated with lower deforestation in neighbouring frontier as well as consolidated municipalities, and no outcome in pre-frontier areas. Increasing the growth in productivity by one standard-deviation (from its median level) is associated with a drop in the change in frontier deforestation of approximately 30% of one standard-deviation. The impact on deforestation in consolidated areas is lower in magnitude but equally statistically significant. This would suggest that, in line with a Bourlaug hypothesis, policies aimed at increasing land yields in cattle ranching are likely to achieve positive environmental outcomes.

Reduced-form models and description of variables

The reduced form equation in (1) is a modified version of the model in Arima et al. (2011). Their model uses a spatial econometric specification that accounts for time variant, spatially indirect effects of soya expansion on deforestation. By using a weights matrix that disentangles the effects of intensification in consolidated areas from local cattle dynamics within the frontier, Equation (1) attempts to test the hypothesis that intensive cattle expansion into degraded pastures in areas of older colonization ends up pushing traditional cattle ranching to the agricultural frontier, hence producing greater deforestation.

Table 2. Variable definitions, descriptive statistics and sources

Variable	Unit	Years	Obs.	Mean (1996)	Relative change[1]	St. Dev.	Source
Deforested area (d*ef*)	Km^2	1997; 2000-2012	589	669.3[a]	2.31[b]	21.83[b]	INPE
prod: land productivity of cattle (*output/pasture*)	R$ / ha / year	1996; 2006	618	0.51	27.87	98.52	IBGE
output: total value of livestock production (bovine, bubaline and other types of grass eating stock animals)	R$ 10^3	1996; 2006	625	6,597.6	0.84	3.36	IBGE
Total *pasture* area, natural and planted	ha	1996; 2006	622	81,531	1.30	11.75	IBGE
Gate *price* of beef[2]	R$	1996; 2006	756	24.2	0.064	$2.86*10^{-6}$	IPEA, IMEA, Seagri, own calculations
Total *cattle* herd	heads	1996; 2006	619	56,855	1.06	4.77	IBGE
Share of land with full land title (*tit*)	%	1996; 2006	623	91.29	0.09	1.13	IBGE
State protected areas (*pr.areas*)	%	1996; 2006	750	2.06	1.19	13.28	Ministry of Environment
Mandatory legal reserve (*LR*)[2]	%	1997; 2006	589	71.5[a]	-0.09[b]	0.14[b]	Forest Code Law, own calculations
Total environmental *fines* / municipality's agricultural output	%	1996; 2006	619	1.90	23.16	124.36	Ministry of Environment, IBGE

Notes: INPE = National Space Research Institute; IBGE = National Bureau of Statistics; IPEA = Applied Economics Research Institute; IMEA = Mato Grosso Institute of Agricultural Economics; Seagri = Secretary of Agriculture, São Paulo; currency in constant 2000 R$.

[1]Unless indicated otherwise, change between 1996 and 2006: $(\bar{x}_{06} - \bar{x}_{96})/\bar{x}_{96}$, where x is is the variable in question.

[2]See appendix 1 for calculation details.

[a]Year = 1997. [b]Base year = 1997.

$$(1) \qquad \ln(\Delta \boldsymbol{def}_{i,f,07-12}) = a_t + \boldsymbol{\beta} \Delta \boldsymbol{W_1 prod}_{i,c,96-06} + c\Delta W_1 price_{i,c,96-06} + d\Delta W_2 cattle_{i,f,96-06} + e\Delta tit_{i,f,96-06} + f\Delta fines_{i,f,96-06} + g\Delta prareas_{i,f,96-06} + h\Delta LR_{i,f,96-06} + \Delta\epsilon_{i,f,07-12}$$

The subscripts i and j denote municipalities; f and c denote frontier and consolidated areas. The link between municipalities i and all other (n-1) municipalities is established by a weights matrix *W*. I create two spatial weights matrices, one based on an Euclidean distance band (W_1) and another that computes the average five nearest neighbours (W_2). The distance matrix links municipalities i to their neighbours j in consolidated areas subject to a maximum threshold distance (m) chosen to allocate at least one neighbour to every frontier municipality (see details in appendix 2). I apply the distance matrix to the variables productivity and farm gate beef prices to obtain a clean measure of productivity of cattle ranching in consolidated areas[6], and apply the 5-neighbours matrix to cattle herd at the frontier to control for local dynamics of cattle. The resulting variables are spatially lagged, average values of productivity, beef prices and cattle herds:

(2) $W_1 prod_{i,f,96} = \sum_{j \neq i}^{n} (w_{1,ij} * prod_{j,c,96})$, where

$$w_{1,ij} = \begin{cases} 1/k \text{ if j is one of } k \text{ nearest neighbours within distance } m \\ 0 \text{ otherwise} \end{cases}$$

(3) $W_2 cattle_{i,f,06} = \sum_{j \neq i}^{n} (w_{1,ij} * cattle_{j,f,06})$, where

$$w_{2,ij} = \begin{cases} 1/5 \text{ if j is one of 5 nearest neighbours} \\ 0 \text{ otherwise} \end{cases}$$

The weighting schemes above are row-standardized, so the resulting spatial lagged variables are weighted averages of the neighbouring municipalities. The use of Euclidean distance as the criterion to establish proximity is justified by the von-Thünean assumption that farmers using traditional methods (low productivity) will locate further away from the areas where intensive agriculture develops, with the key link between rents in separate locations being distance to markets. Ranchers seeking to maximize profits by selling out where land prices are rising and buying new lands in frontier areas will try to minimize distance in order to reduce the costs of moving their herds and households. The assumption

[6] I check for robustness by using an inverse distance weighting scheme, where instead of giving equal weight to each neighbouring municipality a weight equal to the inverse of the Euclidean distance is given. The results are approximately unchanged: the magnitude of the coefficients is larger, but the effect kicks in with a longer time lag (see discussion below). I also use an expanded distance weights band that includes neighbouring municipalities in all clusters: pre-frontier, frontier and consolidated. This alternative specification tests for a more general neighbourhood effect of intensification on deforestation, and the results are compatible with those presented.

that proximity is best captured by Euclidean distance is standard in the spatial econometrics literature, yet an arguably better approach would be to study land use-related migratory patterns and construct a measure of proximity based on migration data, for example. This is an improvement that I intend to implement in the future by using migration data.

The dependent variable, $\ln(\Delta def_{i,f})$, is the change in deforestation between 2007 and 2012 in frontier municipalities. I use 2007 as the baseline because it allows for a one year interval after the treatment (growth in productivity), but I also present robustness checks with other baseline years. The deforestation distribution is skewed to the right, with a high incidence of zero values as well as outliers, so I take the log of the change to improve the model's fit. However, by logging the dependent variable the zero values are dropped, which can bias the results. I run a binary logistic regression to check for the association between the zero values and the treatment. The dependent variable takes value 1 if the change in deforestation equals zero and zero otherwise, and the right-hand side variables are the same as in the main model. The results show no statistically significant association, so logging the dependent variable should generate any bias.

The independent variable and the covariates are all for the inter-census years of 1996 to 2006. The variable measuring the intensification process is $\Delta W_1 prod_{i,f}$, the growth in productivity in the average neighbouring consolidated municipality. Covariates are the following: farm gate beef prices in consolidated areas ($\Delta W_1 price_{i,f}$), containing information on transportation costs to clean the productivity measure out of local specificities; cattle herd in neighbouring frontier municipalities ($\Delta W_2 cattle_{i,f}$), to distinguish local dynamics of cattle expansion within the frontier from the land use process of interest, caused by dynamics in consolidated areas; property rights in frontier areas ($\Delta tit_{i,f}$, a measure of land titling), a key factor that could be influencing both changes in productivity and in deforestation; enforcement of environmental legislation ($\Delta fines_{i,f}$, the total value of environmental fines as a share of total agricultural output), state protected areas ($\Delta prareas_{i,f}$) and the environmental law itself in frontier municipalities ($\Delta LR_{i,f}$, the average share of farms that by law has to be kept forested as a 'legal reserve') (see table 2 for full variable definitions). ϵ is the error term. Changes are calculated after spatially-lagging the variables.

The specification in (4) follows Weinhold and Reis (2008) in adding the levels of the control variables, the initial level of deforestation as well as State dummies (DS_i) to account for fixed effects in the growth rate of deforestation. In case the initial levels are not relevant or have been fully accounted for by fixed effects in levels, the additional controls (highlighted in bold) should be jointly non-significant and the β coefficient should be correspondingly unchanged.

(4) $$\ln(\Delta def_{i,f,07-12}) = a_t + \boldsymbol{DS_i} + \boldsymbol{\alpha}\mathbf{ln}(\boldsymbol{def_{07}}) + \beta \Delta W_1 prod_{i,c,96-06} + \boldsymbol{\beta_1 W_1 prod_{i,c,96}} + c\Delta W_1 price_{i,c,96-06} + \boldsymbol{c_1 W_1 price_{i,c,96}} + d\Delta W_2 cattle_{i,f,96-06} + \boldsymbol{d_1 W_2 cattle_{i,f,96}} + e\Delta tit_{i,f,96-06} + \boldsymbol{e_1 tit_{i,f,96}} + f\Delta fines_{i,f,96-06} + \boldsymbol{f_1 fines_{i,f,96}} + g\Delta prareas_{i,f,96-06} + \boldsymbol{g_1 prareas_{i,f,96}} + h\Delta LR_{i,f,96-06} + \boldsymbol{h_1 LR_{i,f,96}} + \Delta\epsilon_{i,f,07-12}$$

Identification and spatial clustering

If models (1) and (4) were not subject to endogeneity bias, the β coefficients would give the causal indirect effect of land productivity on deforestation and the control variables would assure the conditional independence assumption. The specification I employ approximates the ideal world of full identification by dissociating (lagging) the independent variables from the outcome both spatially and temporally. The problem of simultaneity is thus minimized as the independent variables are time-lagged. Moreover, other types of endogenous causation (any potentially omitted variables) would need to bias the model by simultaneously affecting land productivity in consolidated areas and deforestation at the frontier. This would be less likely to happen, but the specifications also control for fixed endogenous determinants—such as legal constraints or climatic and environmental conditions—affecting the levels of (models 1 and 2) and the change in deforestation (model 2). Finally, measurement error in deforestation leads to downward bias in a fixed effects specification (Griliches and Hausman, 1986).

I cluster municipalities into 3 groups: pre-frontier, frontier and consolidated. Pre-frontier is where a settlement process has not been sparked. Because limited immigration of people and cattle is expected to flow to these municipalities, this cluster works as a counterfactual to the intensification / deforestation process—the statistical coefficients (β) for the indirect land use effect variables are expected to be non-significant, while those for local processes (d) are expected to be significant. Frontier municipalities are where there is a boom in deforestation. Consolidated areas are where settlements are older and deforestation activity lower. The categories are based on deforestation data from the years 2000 to 2004. Pre-frontier municipalities are where deforestation extent (stock) and activity (flow) were low, frontiers are where deforestation extent was low but activity high, and consolidated where deforestation extent was high and activity low.

I follow Rodrigues et al. (2009) and Celentano et al. (2012) in using information on past values of the dependent variable to classify municipalities. Since there is no overlap between the period used for the classification and the time frame used for the outcome variable, this does not configure selection on the dependent variable. I use two alternative measures of deforestation to classify municipalities and obtain comparable results[7]. I also use two alternative classification rules, again with the same results (appendix 3). Moreover, I find a significant overall effect even when I ignore the classification and run the model for all municipalities.

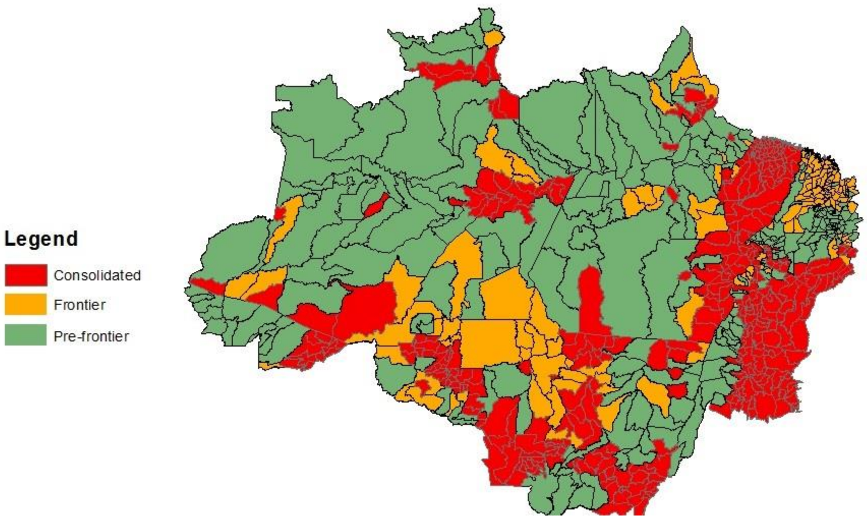

Figure 2. Classification of municipalities into clusters of pre-frontier, frontier and consolidated areas

[7] The deforestation measure provided by INPE only covers forested areas, so I divide the variable deforestation by the total forest cover of each municipality before creating the groups. I use two alternative measures of forested area, one by Embrapa and one by the Ministry of the Environment, thus obtaining two alternative deforestation measures.

I use a panel dataset with 756 municipalities in the Brazilian 'Legal Amazon'[8]. The dataset comprises the two last Brazilian agricultural censuses, 1995/1996 and 2006, including the variables described in table 2. There are two reasons for not using data on previous time periods. First, boundaries have changed a lot until 1997 so going back in time means losing spatial definition as one is forced to aggregate today's municipalities into 'minimum comparable areas'[9]. To be sure, there is nothing intrinsically wrong with trading spatial definition against time variation, but in the particular case of this study there would be a lot to lose and very little to gain: going back in time means blurring out the difference between consolidated and frontier areas as the older municipality boundaries include most of today's consolidated areas. Secondly, the intensification process that I am depicting is a phenomenon of the late 1990s, and the internal context of the Amazon was structurally very different prior to 1994, so there would be little to gain by going back in time.

3. Results

Deforestation is a phenomenon of frontier locations where a process of primitive accumulation takes place by turning idle lands into economic assets. This is consistent with a von-Thünean framework where activities that yield lower rents are pushed to the marginal lands whereas intensive production stays close to central markets. In this paper I am testing the idea that the process of intensification guarantees the reproduction of the frontier and thus of the deforestation dynamics. The results of model 1, where I restrain from controlling for potential fixed effects in the growth rate of deforestation, are consistent with a Boserupian induced intensification framework where farmers migrate to forest margins to maximize the marginal product of labour, as the rapport between land prices and soil fertility is more convenient there. However, when I properly account for initial levels of deforestation, productivity and other controls directly affecting the change in deforestation,

[8] Out of 756 municipalities, 661 have deforestation data for generating group classification, 618 have productivity data for both 1996 and 2006, and 535 have both.

[9] To reduce measurement error, I drop municipalities whose areas (as published by IBGE) have changed more than 5% between 2000 and 2005.

I find stronger and more robust evidence in favour of the competing theory of a benign, land-sparing effect of intensification.

Model 1

The results from model (1) support the hypothesis that intensification in consolidated areas causes increased deforestation. The estimated effect, however, is relatively small, with an extra standard deviation growth in productivity (all else constant, an increase of R$ 7,400,000 in output from 1996 to 2006) being associated with a 0.1 standard deviation supplementary growth in deforestation at the frontier (14.47 Km^2 additional deforestation).

The graphs in figure 3 help to start appreciating the pattern that comes out of the data. Municipalities in frontier areas that are neighbours to municipalities in consolidated areas where productivity has grown between 1996 and 2006 have seen an increased number of cattle purchases. This applies to both quantity and value, as well as growth of cattle herd. At the same time, intensification in consolidated areas has a strong negative association with cattle purchases within consolidated areas, suggesting that productivity is positively associated with cattle herd growth in frontier but not in consolidated areas. In pre-frontier areas, no statistically significant association is found, which is expected since those areas are exogenous to the colonization process that has triggered most livestock and agricultural expansion in the Amazon. Given that cattle is raised at lower stocking rates in frontier areas, these results are consistent with the rebound effect hypothesis as cattle herd growth is expected to imply horizontal expansion.

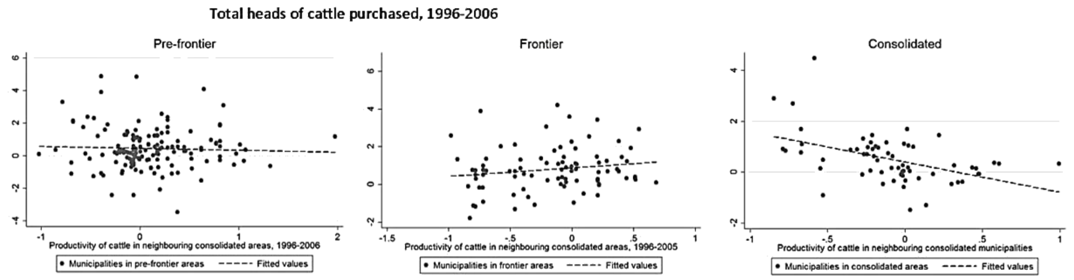

Figure 3. Movement of cattle towards the frontier, 1996-2006

Table 3 indicates that productivity ($\Delta W_1 prod$) had no statistically significant association with frontier deforestation before 2001 (columns 1-3), but that since then the positive coefficient became significant and the model's fit improved (adjusted-R^2 rose from 0.47 to 0.64, columns 4-7), in line with the rebound effect hypothesis. It also shows that the model passes a placebo test, as there's a low model fit and no statistically significant association for the period 97-00 (column 1). Table 4 then shows that the association is robust to including the relevant covariates discussed in section 2, as well as to controlling for baseline year to account for a global shift in the deforestation pattern. Finally, table 5 shows that the statistically significant association only holds for frontier municipalities, with all other areas yielding non-significant results.

Table 3. First difference regression of deforestation on productivity of cattle (OLS), different time frames
Dependent variable: natural logarithm of change in deforestation, frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time frame	97-00	97-12	00-12	01-12	04-12	07-12	10-12
$\Delta W_1 prod$	0.524	0.311	0.369	1.834***	1.540***	0.820*	1.328***
$\Delta W_1 price$	3.499	1.300	1.154	1.998	3.527***	2.297	3.232**
$\Delta W_2 cattle$	2.04e-05***	1.68e-05***	1.61e-05***	1.58e-05***	1.59e-05***	1.59e-05***	1.78e-05***
ΔLR	4.376	11.98***	128***	14.78***	16.09***	16.53***	16.58***
$\Delta title$	0.00310	0.00716	0.00734	0.00137	-0.00327	-0.00321	0.00377
$\Delta pr.areas$	-0.132	-3.262**	-3.758**	-3.458**	-3.111**	-2.452*	-0.958
$\Delta fines$	-0.0338	-0.130	-0.133	0.0308	-0.0149	-0.0237	-0.0332
Year	-1.933	3.663*	3.663*	1.629	-1.614	-0.717	-3.809*
Observations	64	64	64	64	64	64	65
R-squared	0.438	0.531	0.534	0.683	0.715	0.633	0.717
Adj. R-squared	0.357	0.463	0.467	0.637	0.673	0.579	0.676

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics

From table 4 it is evident that the variable farm gate beef price has a modestly positive impact on the coefficient of productivity (columns 1-2). Local cattle herd dynamics in frontier areas significantly decrease the coefficient of productivity (columns 2-3), confirming that the effect of the intensification process needs to be separated from a more localized frontier dynamics effect (as suggested by Arima et al., 2011). The year control shows a negligible impact on regression coefficients (columns 6-7). The environment-related variables have a small downward impact on the coefficient of productivity. For example, taken together, the legal reserve legislation, environmental fines, and the creation of protected areas seem to decrease the attractiveness of a frontier municipality for intensification-related deforestation (columns 5-7).

Table 4. Robustness check. First difference regression of deforestation on productivity of cattle (OLS)
Dependent variable: natural logarithm of change in deforestation (2007-2012), frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\Delta W_1 prod$	1.675***	1.871***	0.390	0.397	1.046**	0.991**	0.979**
$\Delta W_1 price$	—	2.905	0.422	0.411	2.100	2.630	1.984***
$\Delta W_2 cattle$	—	—	2.60e-05***	2.61e-05***	2.17e-05***	2.37e-05***	2.37e-05***
ΔLR	—	—	—	—	17.39***	17.46***	17.19***
$\Delta title$	—	—	—	-0.00159	-0.00206	-0.00220	-0.00215
$\Delta pr.areas$	—	—	—	—	—	0.737	0.301
$\Delta fines$	—	—	—	2.009	—	-0.143	-0.140
Year	3.749***	-0.649	2.003	—	-0.133	-1.003	—
Observations	65	65	65	65	65	65	65
R-squared	0.157	0.186	0.454	0.454	0.543	0.547	0.901
Adj. R-squared	0.143	0.159	0.427	0.418	0.504	0.492	0.889

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Table 5 presents the results of using the full variation in the data to look at the effect of intensification in consolidated areas on deforestation in pre-frontier, frontier and consolidated municipalities. The variable productivity is interacted with the clusters to capture the specific associations within each cluster. For example, the second row of the table indicates that the growth in productivity in consolidated areas has a positive coefficient but no statistically significant association with deforestation in pre-frontier areas. This result is in line with interpreting pre-frontier areas as a counterfactual to the settlement-intensification-migration-deforestation process. The coefficient on change in productivity for frontier areas, as in the previous tables, is statistically significant at the 1% level and in the range +1.5 to +1.74. Finally, the coefficient for consolidated areas is negative but non-significant, suggesting that deforestation is either not impacted or decreased in neighbouring consolidated municipalities as a result of intensification.

Table 5. Robustness check. First difference regression of deforestation on productivity of cattle (OLS), different clusters of municipalities

Dependent variable: natural logarithm of change in deforestation (2007-2012)

	(1)	(2)	(3)
$\Delta W_1 prod$	-0.172	-0.223	-0.376**
$\Delta W_1 prod$*pre-frontier*	0.372	0.139	0.203
$\Delta W_1 prod$*frontier*	1.738***	1.459***	1.686***
$\Delta W_1 prod$*consolidated*	-1.284	-1.685	-1.582
$\Delta W_1 price$	-2.014**	-0.444	1.579***
Year	606***	3.121**	—
All other controls	No	Yes	Yes
Observations	362	362	362
R-squared	0.058	0.408	0.848
Adj. R-squared	0.0369	0.384	0.824

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

The results from model 1 suggest that a given intensification shock in consolidated areas may or may not have a land-sparing effect within consolidated areas, but the effect on frontier areas would be more deforestation. These conclusions, however, are reverted in model 2.

Model 2

Controlling for fixed effects in growth rates affects the conclusion to a major extent, with the evidence of a land-sparing effect being as robust as that of a rebound effect in model 1, but with a stronger association (in the opposite direction) and statistically significant at lower levels. Keeping the 1996 level of productivity in consolidated areas at its median value, an additional growth in productivity of one standard deviation (all else constant, an increase of R$ 7,400,000 in output from 1996 to 2006) is associated with a 0.3 standard deviation reduction in the growth rate of deforestation in frontier municipalities (38.65 Km^2 less deforestation).

I start by showing, in table 6, that a statistically significant association is not found for the placebo test (column 1), nor for periods starting before 2001 (columns 1-3); starting in 2001 the association becomes significant at the 1% level, and the model fit (adjusted-R^2) rises from

0.50 to 0.75 (columns 4-7). The coefficients are consistently negative, suggesting a land-sparing effect with a magnitude in the range of -3.8 and -3. The most interesting piece of evidence in table 6 is an apparent trade-off between the effects of the growth in local cattle herds within the frontier and the change in productivity in the more distant, consolidated municipalities. Up until 2001 (columns 1-3), the change in deforestation was significantly and positively associated with the growth in local cattle herds, but not with the growth in productivity in consolidated municipalities. In the subsequent period, the pattern was inverted.

Table 6. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different time frames. Dependent variable: natural logarithm of change in deforestation, frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time frame	97-00	97-12	00-12	01-12	04-12	07-12	10-12
$\Delta W_1 prod$	-3.861	-2.341	-2.202	-279**	-3.819***	-3.935***	-4.303***
$W_1 prod_{96}$	-2.219	-1.866*	-1.918**	-3.950***	-2.955***	-2.795***	-3.570***
$\Delta W_1 price$	37,202	20,797	17,325	8,326	7,292	8,450	4,685
$W_1 price_{96}$	-2,377	-1,329	-1,107	-532.7	-466.2	-540.2	-299.9
$\Delta W_2 cattle$	2.56e-05**	1.62e-05**	1.53e-05**	-4.80e-06	-1.51e-06	9.95e-07	-3.48e-06
$W_2 cattle_{96}$	-1.81e-05*	-1.06e-05	-1.38e-05**	-1.98e-06	-6.14e-06	-9.50e-06	-7.99e-06
ΔLR	4.723	10.71***	13.55***	8.573	12.18**	12.68***	10.91**
LR_{96}	0.0152*	0.0151	0.0135	0.00303	0.000130	0.000284	0.00673
$\Delta title$	0.0727***	0.0325	0.0215	0.0292	0.0232	0.0260	0.0233
$title_{96}$	-0.136	-0.604	-1.365	-12.41**	-11.48**	-9.655*	-13.45***
$\Delta pr.areas$	-6.810	4.051	6.810	157***	160***	13.90**	18.74***
$pr.areas_{96}$	-0.549**	-0.357**	-0.329**	0.133	0.0627	0.00508	0.0899
$\Delta fines$	13.01***	1.475	-0.492	7.964	1.807	3.911	-1.545
$fines_{96}$	13.01***	1.475	-0.492	7.964	1.807	3.911	-1.545
State dummies	yes	yes	yes	yes	yes	yes	yes
Init. defor. level	yes	yes	yes	yes	yes	yes	yes
Year	24.69	18.19*	17.37*	28.71***	18.88***	16.92***	14.57***
Observations	64	64	64	64	64	64	65
R-squared	0.694	0.682	0.665	0.831	0.835	0.790	0.871
Adj. R-squared	0.541	0.524	0.498	0.746	0.752	0.685	0.803

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Productivity now explains frontier deforestation at the expense of local cattle dynamics (columns 4-7). While the relation between deforestation and local cattle herds is not the focus here, the fact that the coefficient on productivity becomes significant when the one on cattle becomes non-significant suggests that, with a time lag, the impact of the intensification process grows sufficiently strong to dominate the relation with deforestation over local cattle dynamics. This can be seen as evidence that the model is well specified. In fact, in controlling for growth of local cattle herds municipalities within the frontier I am assuming that such growth is not caused by intensification in consolidated areas, otherwise I would be washing away part of the process I am trying to uncover. Yet my assumption is likely to be too strong as any migration process coming from consolidated municipalities through cattle will arguably affect not only frontier municipalities, but also their immediate neighbours. Therefore, by controlling for local herd dynamics I am being overcautious and partially spurring away the effect of interest (appendix 4, columns 1 and 2).

If a triple association between productivity, local cattle herd and deforestation should be expected, then the trade-off that comes out in table 6 suggests that the information in the variable productivity becomes sufficient to account for the full correlation pattern since 2001. Interestingly, this trade-off did not appear in model 1 (see table 3). Why does it manifest in model 2? The reason is the inclusion of the State dummies and initial levels of the control variables (appendix 5). I report F-tests of the joint signification of the fixed effects and they are always highly significant, suggesting that model 2 should be preferred over model 1. The estimated land-sparing effect is robust to excluding most variables from model 2 (appendix 4). The coefficient on productivity remains negative in all cases, and only when the State dummies and most initial level controls are removed (table 7, columns 3-4) does it become non-significant at the 10% level. However, these results are somewhat sensitive to the sample size, as I show in columns 5-6:

Table 7. Robustness check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates). Dependent variable: natural logarithm of change in deforestation (2007-2012), frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta W_1 prod$	-3.724***	-3.723**	-0.910	-0.933	-2.579*	-2.066
$W_1 prod_{96}$	-2.774***	-2.995**	-1.227	-1.539	-2.148**	-2.314**
$\Delta W_1 price$	15,390	14,469	22,460***	2.890	22,989***	2.342
$W_1 price_{96}$	-983.3	-924.6	-1,435***	—	-1,468***	—
$\Delta W_2 cattle$	9.68e-06	1.81e-05	3.52e-05***	2.80e-05***	3.34e-05***	2.76e-05***
$W_2 cattle_{96}$	-1.10e-05	-1.72e-05	-2.74e-05**	-1.26e-05*	-2.45e-05***	-1.12e-05*
ΔLR	111***	17.15***	—	19.69***	—	19.32***
LR_{96}	—	—	10.52***	—	9.339***	—
$\Delta title$	0.000668	0.00121	0.00690	-0.00122	0.00713	-0.00395
$title_{96}$	0.0239	0.0331	0.0349	—	0.0414**	—
$\Delta pr.areas$	-1.954	-8.819	0.877	1.765	1.492	2.746
$pr.areas_{96}$	480	119**	4.030**	—	3.953*	—
$\Delta fines$	-0.0932	-0.239	-0.517**	-0.216	-0.464***	-0.204*
$fines_{96}$	2.516	2.009	-0.951	—	1.364	—
State dummies	yes	yes	no	no	no	no
Init. defor. level (2007)	yes	no	no	no	no	no
Year	11.41	13.84**	0.390	-0.557	3.664	0.277
Observations	65	65	65	65	72	72
R-squared	0.778	0.747	0.665	0.597	0.690	0.619
Adj. R-squared	0.662	0.632	0.579	0.532	0.621	0.563

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Table 8 presents the results of model 2 for each of the three spatial clusters as well as for the full sample. The coefficient on productivity is negative and statistically significant for frontier as well as consolidated municipalities, but non-significant for pre-frontier areas, as expected. The overall effect is thus a net land savings, as in column 4. I analyse the effect of productivity on deforestation in consolidated areas, and find that the coefficients start to be consistently negative and significant from the year 2003 (table 9). This suggests that the intensification process has an indirect impact on frontier deforestation even before (year 2001) it impacts deforestation in the closer, consolidated municipalities (year 2003). Table 9 also shows that, as should be expected, cattle herd dynamics in frontier locations have no impact on deforestation in consolidated areas (however, the opposite is true under model 1).

Table 8. Robustness check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different clusters of municipalities. Dependent variable: natural logarithm of change in deforestation (2007-2012)

	(1)	(2)	(3)	(4)
Municipalities	All	Pre-frontier	Frontier	Consolidated
$\Delta W_1 prod$	-0.720***	-0.155	-475***	-1.785***
$W_1 prod_{96}$	-0.736***	-0.168	-3.964***	-1.696***
$\Delta W_2 cattle$	66e-06*	1.28e-05**	9.42e-06	-9.47e-07
$W_2 cattle_{96}$	-4.21e-06	-3.71e-06	-1.11e-05	-62e-06
Full set of covariates	yes	yes	yes	yes
Init. levels	yes	yes	yes	yes
State dummies	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observations	362	118	72	172
R-squared	0.607	0.683	0.783	0.733
Adj. R-squared	0.579	0.601	0.679	0.689

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Table 9. Robustness check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different time frames. Dependent variable: natural logarithm of change in deforestation, consolidated municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time frame	97-12	02-12	03-12	04-12	06-12	07-12	08-12	10-12
$\Delta W_1 prod$	-0.509	-0.431	-0.999**	-1.067**	-1.283**	-1.503**	-1.989***	-1.696**
$W_1 prod_{96}$	-0.740	-0.779*	-1.158***	-1.177***	-1.256**	-1.473***	-1.932***	-1.821***
$\Delta W_2 cattle$	-9.47e-07	-1.21e-06	-7.93e-07	9.28e-08	-1.49e-07	-1.76e-06	-1.26e-06	-2.30e-06
$W_2 cattle_{96}$	1.45e-06	-3.58e-06	-71e-06*	-52e-06*	-3.72e-06	-4.14e-06	-7.06e-06*	-3.91e-06
Full set of covariates	yes	yes	yes	yes	yes	yes	yes	yes
Init. levels	yes	yes	yes	yes	yes	yes	yes	yes
State dummies	yes	yes	yes	yes	yes	yes	yes	yes
Year	yes	yes	yes	yes	yes	yes	yes	yes
Observations	159	159	159	159	159	159	159	163
R-squared	0.724	0.788	0.798	0.780	0.760	0.733	0.690	0.691
Adj. R-sq.	0.675	0.750	0.762	0.740	0.717	0.686	0.634	0.637

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

The comparison between models 1 and 2 is clearly in favour of the latter. While both pass a placebo test that looks at the impact of growth in productivity between 1996 and 2006 on deforestation between 1997 and 2000, model 2 includes control variables that make theoretical sense, are jointly significant according to an F-test, and produce results that are in line with theory, particularly with regards to the roles of local cattle herd dynamics versus intensification in consolidated municipalities. Moreover, model 1 gives a counterintuitive result when estimated over consolidated municipalities: the coefficient on cattle herd dynamics in frontier locations is consistently positive and significant, suggesting a spatial effect that runs from frontiers to consolidated areas, counter to what should be expected and to the results from model 2.

Controlling for the initial level of productivity causes the coefficient on productivity growth to change signs. The State dummies increase the significance of the negative coefficient, while all other initial levels have only a minor impact on the results. This suggests that the results in model 1 are biased by the omission of the initial level of productivity, and that the mechanism linking intensification to frontier deforestation depends on initial levels. The initial level of productivity is negatively correlated with both the change in deforestation and productivity growth, so its omission led to an upward bias. All in all, the evidence presented under model 2 points to a strong land-sparing effect caused by intensification in consolidated areas. The effect on deforestation in frontier areas is already strong, but I find that deforestation in consolidated municipalities is also reduced.

4. Conclusion

Two competing predictions for the effect of land use intensification on deforestation have been proposed in the literature: an optimistic hypothesis that more productive land uses will spare land for nature, and a less optimistic scenario that suggests a displacement effect from localities closer to markets towards forest margins. Evidence allowing for the discrimination between these alternative hypotheses has been thin so far, especially in what relates to cattle ranching. Given the relevance of livestock raising for land use change across the world, this paper analyses the outcomes of the intensification process in the Brazilian Amazon.

Intensification of cattle ranching takes place mostly in consolidated areas, where markets have deepened and the initial, pioneering phase of the colonization process gave way to a more established society and economy. The main factor that explains the process of land use intensification is enforcement of a command-and-control legislation that places a high toll on land clearings, thus incentivizing farmers to adopt land-sparing technologies. Any stimulus to use land more productively, however, becomes weaker as distance from markets increase, due to lower enforcement of the law as well as high transportation costs curtailing profits. Deforestation due to horizontal agricultural expansion is therefore more likely in frontier locations.

I use data from a 16-year period to test for an indirect land use effect of cattle ranching on deforestation in the Amazon. I categorize municipalities into pre-frontier, frontier and consolidated clusters and look for an association between productivity of cattle in consolidated areas and deforestation in frontier locations. I employ Euclidean distance weights matrices to establish the link between frontier municipalities and their neighbouring municipalities in consolidated areas. Based on a conventional von Thünean approach, an intensification shock in consolidated areas is expected to have a stronger effect on spatially closer frontier municipalities, and a much weaker effect on locations further away. Under this assumption, I run a first-difference model to look for evidence a rebound effect.

I start by adapting the spatial econometric model by Arima et al. (2011) to the case of livestock intensification. Using appropriate controls that include information from frontier municipalities, such as protected areas and property rights, as well as factors from consolidated areas, such as farm gate beef prices, the model suggests a small positive effect of productivity of cattle ranching on deforestation, in line with the rebound effect hypothesis. The results would indicate that changes in productivity in frontier locations are positively associated with migration of cattle to frontier areas and negatively associated with migration of cattle to consolidated areas. Furthermore, the regression results produce a consistently positive and statistically significant coefficient on the intensification variable.

A key contribution of this paper is to improve the empirical analysis by adapting the framework in Weinhold and Reis (2008) to the indirect land use effect problem being tested here. I add State fixed effects and initial levels affecting the growth rate of deforestation, thus producing a more coherent framework to test the inherently dynamic hypothesis of a rebound effect. The inclusion of fixed effects directly affecting the growth rate is justified by the presumption that the standard fixed effects in levels is likely to leave out omitted variable bias coming from, for example, the initial level of productivity in consolidated areas affecting the growth rate of deforestation at the frontier through a channel other than the levels of deforestation. I test for the joint significance of the additional controls by running F-tests and the results are in favour of keeping the variables. Moreover, their inclusion changes the results drastically, suggesting that the assumed role of fixed effects in growth rates is indeed important.

The conclusions from the initial model are now reverted and the evidence points consistently to a substantial land-sparing effect of land use intensification. I run a placebo test by estimating the impact of the change in productivity from 1996 to 2006 on the change in deforestation from 1997 to 2000. The resulting coefficient on productivity is not statistically significant, as expected. I run the model for different time frames of the growth in deforestation, starting from 1997 to 2012 until 2010 to 2012, and the effect of productivity starts to be significant from the year 2001, consistent with the idea that there is a time lag. Moreover, there is a clear trade-off between the indirect land use effect coming from distant consolidated areas and the effect of cattle herd growth in the nearest five frontier municipalities. The latter variable becomes non-significant exactly in 2001, suggesting that the effect of productivity becomes sufficiently strong to dominate the indirect effect-related covariance structure.

I run robustness checks to test for the sensitivity to control variables, and the results are consistently robust to dropping control variables in different combinations. I also implement a second placebo test by running the model for pre-frontier municipalities, where the intensification process is expected to have no impact, and the result is as expected. Lastly, I look for more generalizable versions of the model by running it for deforestation in consolidated municipalities, and find that there is an equally robust and statistically significant land-sparing effect, only with a lower magnitude and with a longer time lag (the coefficient starts to be significant in the year 2003).

How strong are the econometric results to allow for a rejection of the rebound effect hypothesis? Given the robustness of the results I obtain, they are a firm suggestion that a land-sparing effect should be taken seriously. Moreover, since the measure of deforestation I use does not capture reforestation or forest regrowth, the possibility of lands previously cleared being abandoned and thus taken for a reduction in deforestation is ruled out. However, my methodological approach innovates in some ways with respect to existing approaches, so the results should need replication and further scrutiny.

For example, it would be important to try alternative ways of classifying frontiers and consolidated areas. One possibility would be to use the fact that frontier areas tend to see a rapid growth in the area planted with rice, while the consolidation process sees a trade-off between rice and pasture, to distinguish frontiers from consolidated areas. Using rice instead of deforestation would address any remaining concern of selection on the dependent variable. Another improvement would be to use inter-municipality migration data to construct the spatial weights matrix, as the Euclidean distance-based approach may be too crude a way of capturing the spatial pattern of migration.

The provisional conclusion is that productivity growth in consolidated areas can save forests. How does this happen? While the exact mechanism of a land-sparing effect remains unclear, some suppositions can be advanced. The results indicate that the intensification process in consolidated areas first reduces deforestation at the frontier, then reduces deforestation in consolidated areas. This timing suggests that farmers in consolidated areas are initially prevented from out-migrating, reducing deforestation in frontier areas since 2001, but keeping the deforestation pattern unchanged in consolidated areas until 2003, when farmers eventually revert to intensification or migrate to urban areas.

Cattle ranchers in the Amazon are to a large extent price takers, who respond to mostly exogenous output price signals. Once they switch from a traditional production function that relies heavily on horizontal expansion to a more intensive production function, demand for land will decrease at the same time as demand for other production factors (including labour) will increase. An important parcel of farmers, however, are left out of the intensification process, and given the effect that it has on land prices, part of those laggard farmers will at some point resort to out-migration, either to urban areas or to frontiers. The effect on deforestation then depends on the pattern of the resulting migration. For example, the out-migration process can be segmented at the household level, with some members of the family going to the frontier while others head to urban or peri-urban areas. This segmentation may lead to a different pattern of land use at the frontier, but further research is needed to uncover the mechanism linking the intensification process to a land-saving effect at the frontier.

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Appendices

Appendix 1. Variable calculations

Gate beef prices

This variable is traditionally measured by CEPEA (Centro Paulista de Estudos Agropecuários) for a few trading centres in Brazil, including São Paulo, Campo Grande and Cuiabá. The time series is available starting in 2003, but prices for São Paulo are available since 1995 (Seagri, Secretaria da Agricultura), so I predict the prices for Cuiabá in 1996 using the time-series:

$$price_{Cuiaba,t} = \alpha + \beta price_{SP,t} + \varepsilon_t$$

One agricultural consultancy in the State of Matro Grosso (IMEA, Mato Grosso Institute of Agricultural Economics) has published daily estimates of the price of finished cattle (R$ / 30 Kg) for a number of cities in Mato Grosso since 2011.

I use the IMEA time series to estimate the following regression:

$price_{m,t} = \alpha + \beta price_{Cuiaba,t} + \varepsilon_t$, where m are 4 municipalities in Mato Grosso.

Based on (2) and the Cuiabá data for 2006 and 1996 obtained in (1), I predict the prices for 4 municipalities in Mato Grosso. Next I use the variable distance to State capita (*dist*) provided by IBGE to estimate a model of *price* on distance:

$$price_{m,t} = \alpha + \beta dist_{m,t} + \varepsilon_i$$

I use the estimated coefficients to predict the prices for all municipalities in Mato Grosso for the years 1996 and 2006.

Finally, I use the variable transportation costs (*tcost*) to São Paulo (IPEA) to estimate the following cross-sectional model:

$price_i = \alpha + \beta tcost_i + \varepsilon_i$, where i are all municipalities in Mato Grosso.

The estimated coefficients give me the association between transportation costs to São Paulo and prices, for 1996 and for 2006. I use these to predict the prices in all other municipalities in the Amazon.

Mandatory legal reserve

I use the percentages specified in the law for the years 1965, 1996, 1997, 1998, 2000 and 2005, and the spatial variation according to vegetation type–forests, savannahs, amazonic grasslands–political boundaries–North Region, Legal Amazon–and agricultural zoning (for the State of Rondônia). I overlay shapefiles of vegetation type (Embrapa) and protected areas (Ministry of Environment, 1996 and 2006) to calculate the share of the private lands in each municipality that is available for agricultural exploitation according to the law.

Appendix 2. Euclidean distance band weighting scheme

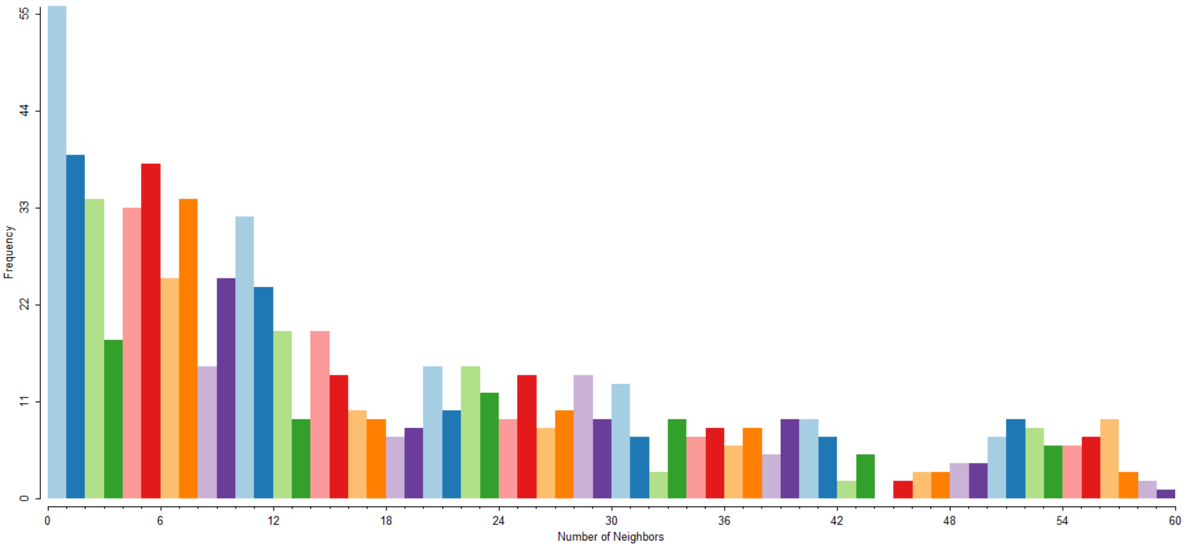

Figure 1. Connectivity histogram from distance weighting. This figure shows the result of the weighting scheme I adopt in matrix W_1 in terms of frequency of neighbours. W1 reads from the group of consolidated municipalities to determine which ones are neighbours to frontier municipalities. The histogram shows that at least 50 frontier municipalities have been allocated only 1 neighbour in consolidated areas.

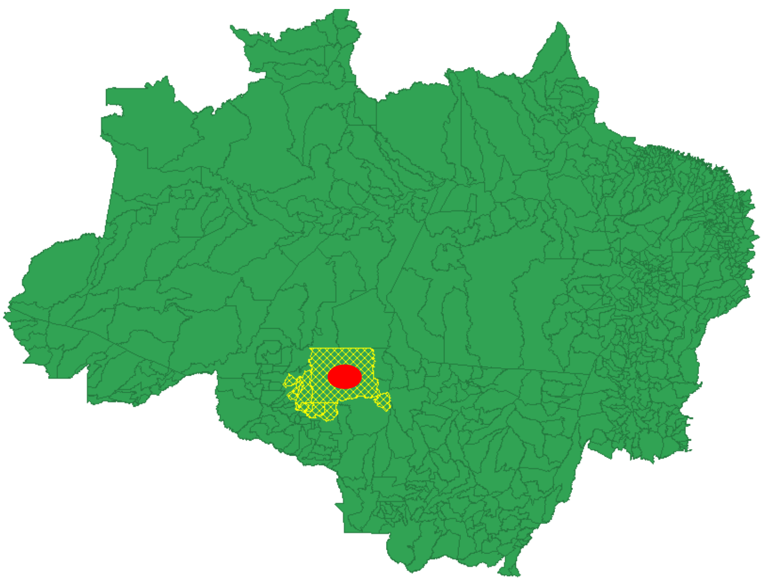

Figure 2. Example of one frontier municipality (red circle) and its neighbouring consolidated municipalities (yellow)

Appendix 3. Creation of pre-frontier, frontier and consolidated clusters of municipalities

I use the variables def04 and def00, equal to the extension of deforestation (km^2) divided by the total forested area in each municipality in the years 2004 and 2000.

I define the variable MTE1 (municipality's total extension 1) equal to 1 where the total extension of deforestation was lower than the minimum value between all municipalities plus 2/3 of the difference between the minimum and the mean:

MTE1=1 if def04<=(r(min)+((r(mean)-r(min))/1.5)) ; MTE=0 otherwise

I define the variable MTA1 (municipality's total activity) equal to 1 where deforestation activity between 2000 and 2004 was lower than the median between all municipalities:

MTA1=1 if def00_04<=r(p50)

From this I create the clusters as follows:

prefrontier=1 if MTE1==1 & MTA1==1 ; prefrontier=0 otherwise

frontier=1 if MTE1==1 & MTA1==0 ; frontier=0 otherwise

consolidated=1 if MTE1==0 & MTA1==1 ; consolidated=0 otherwise

I do this procedure in two alternative ways: I either use the mean, median, minimum and maximum values of the full population of municipalities, or I do it separately by State. The latter is the one I use in the main model.

Appendix 4. Robustness check. First difference regression of deforestation on productivity of cattle, (OLS, including fixed-effects in growth rates).
Dependent variable: natural logarithm of change in deforestation (2007-2012), frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta W_1 prod$	-3.724***	-4.192***	-3.361**	-3.181**	-4.416***	-4.058***	-1.656***	-2.591***
$W_1 prod_{96}$	-2.774***	-2.988***	-2.515***	-2.512***	-2.826***	-2.691***	-1.381***	-2.709***
$\Delta W_1 price$	15,390	8,097	1,915	1,562	4,467	-4.201**	—	—
$W_1 price_{96}$	-983.3	-517.5	-122.5	-99.92	-285.7	—	—	—
$\Delta W_2 cattle$	9.68e-06	—	—	—	—	—	—	—
$W_2 cattle_{96}$	-1.10e-05	—	—	—	—	—	—	—
ΔLR	15.11***	12.12***	—	—	—	—	—	—
LR_{96}	—	—	7.868***	8.081***	—	—	—	—
$\Delta title$	0.000668	-0.000244	-0.000835	—	—	—	—	—
$title_{96}$	0.0239	0.0200	0.00532	—	—	—	—	—
$\Delta pr.areas$	-1.954	-2.908	0.640	—	—	—	—	—
$pr.areas_{96}$	5.480	5.964	2.061	—	—	—	—	—
$\Delta fines$	-0.0932	0.0926	0.157**	—	—	—	—	—
$fines_{96}$	2.516	3.042	-3.311	—	—	—	—	—
State dummies	yes	yes	no	no	no	no	no	no
Init. deforest. (2007)	0.0996	0.124	0.500***	0.515***	0.622***	0.633***	0.603***	—
Year	11.41	9.174	-1.710	-1.135	9.618	6.343**	-0.114	4.374***
Observations	65	65	65	65	65	65	65	65
R-squared	0.778	0.771	0.593	0.574	0.500	0.498	0.469	0.278
Adj. R-squared	0.662	0.667	0.499	0.530	0.458	0.464	0.443	0.255

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

Appendix 5. Specification check. First difference regression of deforestation on productivity of cattle (OLS, including fixed-effects in growth rates), different time frames.
Dependent variable: natural logarithm of change in deforestation, frontier municipalities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time frame:	00-12	00-12	01-12	01-12	00-12	00-12	01-12	01-12
$\Delta W_1 prod$	-0.00416	0.390	1.808***	1.459**	-0.218	-1.793	-2.400	-6.018***
$\Delta W_2 cattle$	1.61e-05***	1.23e-05***	1.59e-05***	1.20e-05**	2.12e-05***	1.61e-05**	8.56e-06	-5.02e-06
Year	3.287*	2.216	1.040	0.631	9.137*	16.82**	12.23*	24.79***
Init. levels	no	no	no	no	yes	yes	yes	yes
State dummies	no	yes	no	yes	no	yes	no	yes
F-test on state dummies (p-value)	—	0.0001	—	0.0001	—	0.0014	—	0.0013
F-test on state dummies and initial levels (p-value)	—	—	—	—	—	0.0001	—	0.0001
Observations	76	76	76	76	76	76	76	76
R-squared	0.537	0.619	0.625	0.669	0.589	0.647	0.697	0.752
Adj. R-squared	0.485	0.521	0.580	0.579	0.487	0.500	0.621	0.643

*** p<0.01, ** p<0.05, * p<0.1

Robust t-statistics.

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