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# The role of pasture and soybean in deforestation of the Brazilian Amazon

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## Abstract

The dynamics of deforestation in the Brazilian Amazon are complex. A growing debate considers the extent to which deforestation is a result of the expansion of the Brazilian soy industry. Most recent analyses suggest that deforestation is driven by the expansion of cattle ranching, rather than soy. Soy seems to be replacing previously deforested land and/or land previously under pasture. In this study, we use municipality-level statistics on agricultural and deforested areas across the Legal Amazon from 2000 to 2006 to examine the spatial patterns and statistical relationships between deforestation and changes in pasture and soybean areas. Our results support previous studies that showed that deforestation is predominantly a result of pasture expansion. However, we also find support for the hypothesis that an increase of soy in Mato Grosso has displaced pasture further north, leading to deforestation elsewhere. Although not conclusive, our findings suggest that the debate surrounding the drivers of Amazon deforestation is not over, and that indirect causal links between soy and deforestation may exist that need further exploration. Future research should examine more closely how interlinkages between land area, prices, and policies influence the relationship between soy and deforestation, in order to make a conclusive case for ‘displacement deforestation’.

**Keywords:** soybean, pasture, deforestation, Amazon, geographic patterns

 Online supplementary data available from [stacks.iop.org/ERL/5/024002/mmedia](http://stacks.iop.org/ERL/5/024002/mmedia)

## 1. Introduction

Agricultural land-use changes have been the major driving force behind land-cover transformation in Latin America. Economic development in the region, international market demand, and government policies, have led to the transformation of natural ecosystems into agricultural land and the intensification of land use (Barbier 2004, Heyck and Lynn 2002, Nepstad *et al* 2006).

Brazil, in particular, has witnessed rapid land-cover changes in recent decades (Lepers *et al* 2005). Since the late 1970s, supported by state subsidies and facilitated by massive infrastructure development, the Brazilian Amazon has

experienced large-scale forest conversion and colonization for cattle ranching, particularly along the ‘arc of deforestation’ (Lambin *et al* 2003, Houghton *et al* 1991, Fearnside 2007, Rudel 2005). However, over the last decade, export crops have gained increasing prominence, causing substantial changes in land use and cover (Brown *et al* 2004, Fearnside 2001, Chomitz and Thomas 2001, Smith *et al* 1998). In the 1990s, market liberalization triggered the increase of overall agricultural production. Expanding world markets, improved access to local credit, and government incentives such as tax exemptions, funding of agricultural research, and improved marketing channels and infrastructure, rapidly encouraged the expansion of export crops (Valdes 2006, Brown *et al* 2004, Barbier 2004, Madi 2004). The Brazilian agro-business sector has intensified agricultural land use, increasing large-scale

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mechanization and improving farm productivity, and become more competitive (Kaimowitz and Smith 2001, Mueller 2003).

Today, Brazil is one of the world's largest exporters of agricultural and food products. Global demand for soybean oil and soybean meal, which are mainly used in high-protein animal feed and as refined cooking oil, has increased the demand for Brazilian soybean, particularly from China (FAO 2009, Ash 2000). In response, soybean cultivation has increased significantly in Brazil, making this crop the most important in terms of harvested area since the 1990s.

The increasing role of large-scale agriculture and the vast remaining potential for expansion of farming in Amazonia (USDA 2003) is causing much concern about deforestation and the loss of ecosystem goods and services (Foley *et al* 2007, Fearnside 2005, Morton *et al* 2006). According to the Brazilian National Institute for Space Research (INPE, its Portuguese acronym), 18.9 million hectares were deforested in the Legal Amazon during 2000–2006 (INPE 2007). Just what is driving the recent deforestation in Brazil is a matter of growing debate. Some observers suggest that much recent deforestation is related to the expanding soybean sector (Fearnside 2005, Bickel and Dros 2003, Carvalho *et al* 2002), but others dispute this claim, and argue that soybean is expanding into land previously under pasture, and not causing new deforestation (Mueller 2003, Brandao *et al* 2005).

A small number of recent studies have examined this issue more carefully using satellite remote sensing technology. Morton *et al* (2006), using an analysis of 250 m resolution MODIS satellite scenes, found that the expansion of cropland (mainly soy) into areas previously covered by forest had become one of the main causes of deforestation in the state of Mato Grosso, contributing to 17% of the total forest loss during 2000–2004. The study also pointed out that, between 2000 and 2003, there was a shift in deforestation dynamics in Mato Grosso, with the direct conversion of forest to pasture decreasing from 78% to 66%, whereas the conversion of forest to crop areas increased from 13% to 23%. Brown *et al* (2005) used 30 m resolution Landsat imagery in the Vilhena municipality of Rondônia to evaluate the land-cover changes accompanying soybean production during 1996–2001. They found that while some conversion of forest to soy occurred, most of soybean expansion was occurring through the slight expansion of existing fields or through conversion of already deforested land. A more recent study by an environmental organization and a soybean trade group analyzed 250 m resolution MODIS scenes containing 630 sample areas of deforested land in Mato Grosso, and found that only 12 sample areas (0.88% in terms of area) were in soy cultivation, while nearly 200 were converted to pasture land (32% in terms of area) (Greenpeace-Brazil 2009). These recent studies have contributed new evidence to the debate on the role of soybean cultivation in Amazon deforestation. The current consensus seems to be that while some forest conversion to soy is occurring, the majority of deforestation is destined for cattle pasture formation and ranching (Morton *et al* 2006, Brown *et al* 2005, Greenpeace-Brazil 2009).

Despite substantial commentary about the relationships between agricultural land use and deforestation in Amazonia,

few comprehensive large-scale studies are available of the geographic patterns of land-cover change. Such studies are necessary in order to understand the potential spatial shifts in land use from one region to another, in addition to the *in situ* land-use dynamics mainly studied hitherto. Policies targeting reduced deforestation will need to have a good understanding of the main underlying causes and dynamics of deforestation (including the proximate versus underlying causes). In the Amazon, the picture remains cloudy about the role of ranching versus large-scale soybean expansion.

Here we use municipality-level statistics across the Legal Amazon to examine the spatial patterns, statistical relationships, and potential spatial shifts in land use over the period 2000–2006.

## 2. Methods

This study covered the nine states comprising the Brazilian Legal Amazon (not all municipalities of Maranhão and Tocantins, however, fall within the official borders of the Legal Amazon). We obtained annual census data at the municipality level on deforestation, crop harvested areas, and livestock population for the Legal Amazon from 2000 to 2006 from various sources. Census data on pasture were available only for 1996 and 2006 (IBGE 2006), and estimated annually for the 2000–2006 period based on livestock data. The data sources and estimation procedures are described in detail below.

### 2.1. Developing consistent administrative boundaries

Brazil has witnessed significant changes in territorial administrative boundaries over time, particularly in the Amazon where new settlement and population growth beget administrative division of larger territories into small ones. Changes in municipality areas have affected up to 50% of the area in some states. Between 2000 and 2006, however, the changes were minimal, with the number of municipalities in the Brazilian Amazon increasing by 16. This small change nevertheless poses a problem when using census data to carry out inter-municipal spatial analysis of land-cover changes over time.

We, therefore, developed a consistent administrative boundary data set using GIS and database techniques. The Brazilian Institute of Geography and Statistics (IBGE, its Portuguese acronym) provided geographic data on administrative boundaries for different years (1991, 1994, 1997, 2001, and 2005) in *shapefile* format (IBGE 2007). These *shapefiles* were used to: (1) identify changes in administrative boundaries and (2) create a database that contained the historical changes when they occurred. The 2005 version contained the largest number of administrative units for the Brazilian Amazon and was therefore used as the starting point for analysis. Using GIS techniques (overlay of different *shapefiles*, multiple queries and selection) the new municipalities established each year were identified. The overall objective was to find the largest administrative unit

(or sometimes groups of administrative units) that could be consistently mapped over the entire 1990–2006 period<sup>4</sup>.

The new geographic areas were defined using the following two rules. (1) If an administrative unit was split at any given time into smaller units, the larger unit from the previous time periods was chosen to represent the data. The tabular data from the smaller units in later time periods were aggregated and assigned to the administrative boundary of the larger unit. (2) Sometimes new municipalities were created by combining several areas of different municipalities where the new municipality boundary cut across old boundaries. In this case both the tabular data and the *shapefiles* were aggregated to create a larger pseudo-administrative unit that was consistent over time.

The different tabular datasets (crops, livestock, pasture, and deforestation) were then consistently integrated into the new spatial representation of administrative units for the Legal Amazon (444 municipalities in the final database). Additional attention needed to be paid when merging the shapefile with the tabular data because, although the names of municipalities did not change, sometimes their administrative borders did.

## 2.2. Compiling census data on land use

**2.2.1. Deforested area.** The National Institute for Space Research in Brazil has been monitoring the deforestation of the Brazilian Amazon using Landsat Thematic Mapper data since 1974 (INPE 2007). Over the last 10 years, the PRODES project of INPE ([www.obt.inpe.br/prodes/](http://www.obt.inpe.br/prodes/)) has developed a methodology to more accurately determine the increase of deforested areas in the Amazon (Camara *et al* 2006). We obtained raster data on deforested areas between 2000 and 2006 from PRODES, and converted them to a vector database at the municipality level using GIS.

**2.2.2. Harvested area of crops and livestock population.** The SIDRA database (Sistema IBGE de Recuperação Automática: [www.sidra.ibge.gov.br/](http://www.sidra.ibge.gov.br/)) of the IBGE provides annual data on planted area, harvested area, value of production, and other variables for perennial and annual crops (IBGE 2006). These data are based on estimates, and not censuses, founded on expert surveys. We obtained harvested area statistics for the Legal Amazon at the municipality level for soybean, maize, rice, cassava, cotton, beans, sugarcane and wheat, the eight largest crops in terms of area harvested. The other crops found in lower proportions were grouped into a single category, ‘Other crops’. Tabular data were compiled from the website for the period 2000–2006. From the IBGE-SIDRA database, we also obtained municipality-level data from 1996 to 2006 on the number of heads of livestock (cattle, horses, mules, buffalos, donkeys, goats, and sheep).

**2.2.3. Pasture area.** The main source of information on area under pasture is the agricultural censuses conducted every five or ten years by the IBGE. The most recent data are available for

1996 and 2006 at the municipality level. Data on pasture area are unavailable on an annual basis, but areas were estimated for the years 2000–2006 using data on livestock numbers. First, livestock stocking density was calculated for the two years for which information was available on both area under pasture and livestock numbers (1996 and 2006). Then the stocking density was linearly interpolated between these two dates and lastly, pasture area data were estimated for 2000–2006 in each municipality as a function of estimated annual stocking density and livestock numbers.

Because not all animals are the same size or weight, or consume the same amount of forage, we normalized livestock data using an ‘animal unit equivalent’ in order to correct them for the differences in land area used by different animal species (Scarnecchia 2004). The Brazilian Ministry of Agriculture has developed, for three different regions of Brazil, a standard conversion factor (Ramos 2005).

The livestock data were converted to total livestock units using the corresponding regional animal unit conversion factor for the 1996–2006, as follows:

$$TLU(i, t) = \sum_k N(i, t, k) f_{AU}(i, k),$$

where  $TLU(i, t)$  is the total livestock units for municipality ‘ $i$ ’ and year ‘ $t$ ’,  $N(i, t, k)$  is the number of animals in each municipality of animal type ‘ $k$ ’ and  $f_{AU}$  is the animal unit conversion factor (assuming that all municipalities within each region with data have the same conversion factor).

We then calculated livestock stocking density for 1996 and 2006 as follows:

$$LSD(i, t) = TLU(i, t) / P(i, t), \quad t = 1996, 2006$$

(units = livestock units ha<sup>-1</sup>),

where  $LSD$  = livestock stocking density for each municipality,  $TLU$  = total livestock units, and  $P$  = total area under pasture for 1996 and 2006 from the census data (ha).

Once the livestock stocking density for 1996 and 2006 was calculated, i.e.,  $LSD(i, 1996)$  and  $LSD(i, 2006)$ , we estimated stocking density for 2000–2006 using linear interpolation:

$$LSD(i, t) = LSD(i, 1996) + \frac{LSD(i, 2006) - LSD(i, 1996)}{(2006 - 1996)} \times (t - 1996), \quad t = 2000, 2001, \dots, 2006.$$

We then estimated the area under pasture for 2000–2006 using:

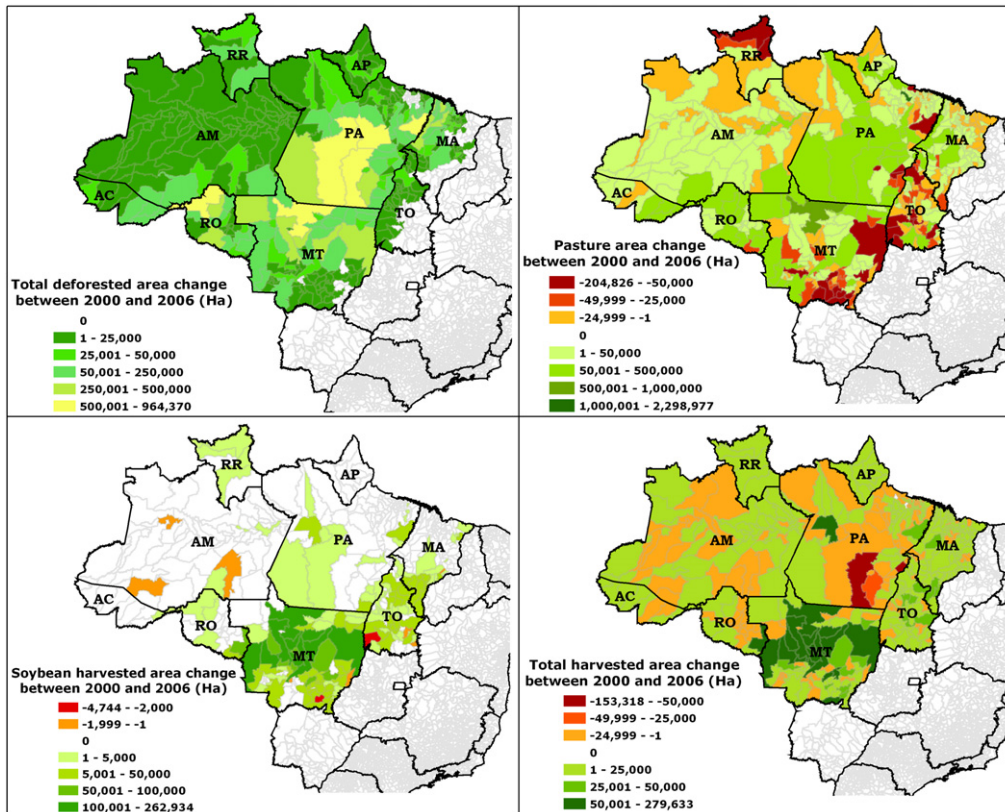
$$P_{est}(i, t) = \frac{TLU(i, t)}{LSD(i, t)}, \quad t = 2000, 2001, \dots, 2006.$$

Our estimates show that while total livestock units increased by 34% (from 47 million to 72 million) between 2000 and 2006, pasture only increased by 20% (from 49 million ha to 61 million ha) because of the increasing stocking density (from 0.74 to 1.17 livestock units ha<sup>-1</sup>).

## 2.3. Analysis

To investigate the relationship between agricultural expansion and deforestation during 2000–2006, census data at the municipality level were compared using ordinary least

<sup>4</sup> Even though this paper only covers the 2000–2006 period, our administrative boundary database was developed to be consistent over the 1990–2006 time period for performing other longer-term analysis.



**Figure 1.** Changes in area of different land uses in the Legal Amazon from 2000 to 2006.

squares (OLS) linear regression model. We used both simple and multiple linear regression to examine the statistical relationship between the following variables: (a) deforestation, (b) change in soybean area, and (c) change in pasture area over the 2000–2006 period, with all variables being normalized by the total area of each municipality. Because of the lower quality of municipality statistics on annual crop and pasture areas, based typically on expert surveys, we assessed changes in area over 2000–2006 by calculating the slope of a trend line fitted through the data, rather than simply taking the difference between 2000 and 2006; such an estimate would be more robust to anomalous individual years of data.

It was difficult to discern a direct relationship between agricultural change and deforestation in those municipalities in the southern and eastern Amazon, where a large proportion is under ‘cerrado’ vegetation or natural savanna. Agricultural area in the cerrado region has certainly increased without replacing forest. Therefore, we restricted our statistical analysis to those municipalities with more than 50% forest cover in 2000, thus capturing land-cover change on the extensive margin. The statistical analysis was initially conducted for the entire Legal Amazon, and then separately for the three states most responsible for deforestation: Mato Grosso, Para and Rondônia.

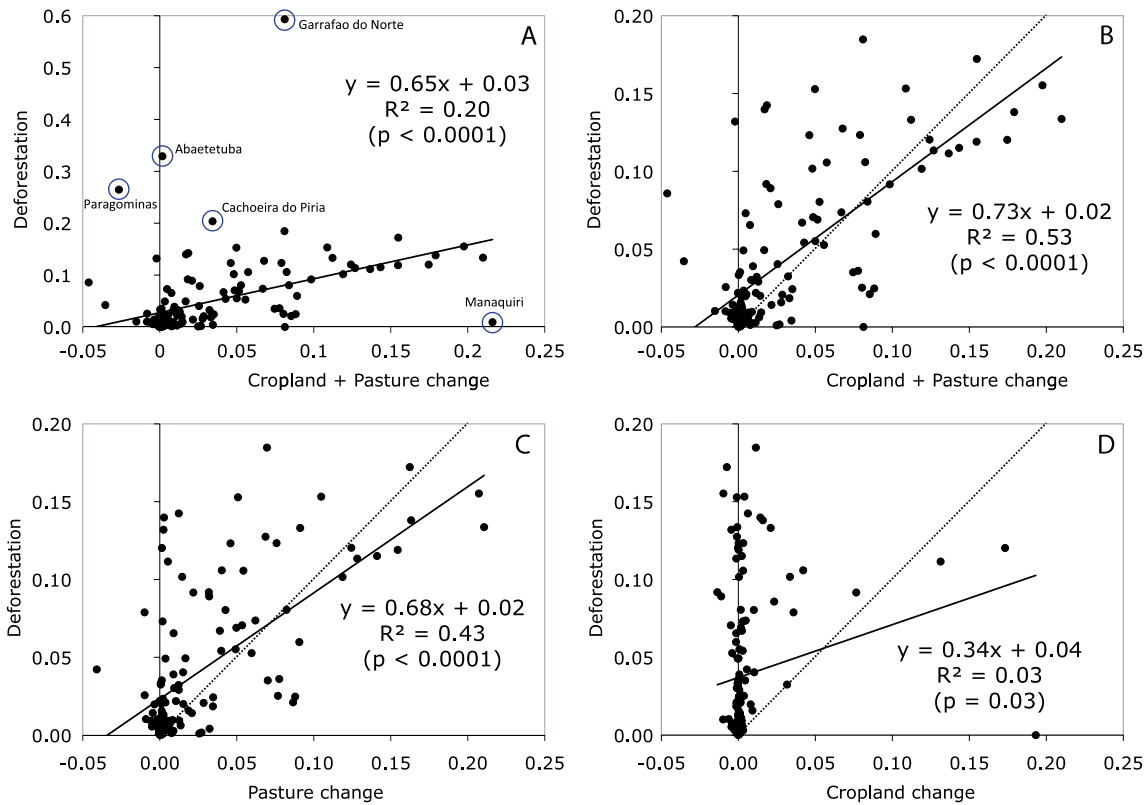
To better understand the spatial shifts in both deforested and agricultural areas in the Legal Amazon, a centroid analysis was performed. This involved two steps: (1) determination of the centroid of each municipality; and (2) calculation of the weighted mean centroid over the entire region, where

the weights are the areas of land use under consideration (deforested area, total pasture area, and total soybean area) for each municipality. The weighted mean centroid is therefore located nearest to those municipalities with the largest land-use area.

To further explore the spatial relationships, and potential land-use shifts in agriculture and deforestation, we labeled all the municipalities of the Legal Amazon according to their predominant land-use transitions over the 2000–2006 period:

- (1) Municipalities with deforestation and increase in pasture (if both pasture and soy increased, only those municipalities where pasture increase > soy increase were selected).
- (2) Municipalities with deforestation and increase in soy (if both pasture and soy increased, only those municipalities where soy increase > pasture increase were selected).
- (3) Municipalities showing increase in soybean and decrease in pasture (if both pasture and forest decreased, only those municipalities where pasture decrease > forest decrease were selected).
- (4) All other municipalities.

Finally, we examined the statistical relationship between deforestation and the price of soy and cattle over the 1995–2007 period. Annual deforestation data for the Legal Amazon were obtained from PRODES, while the data on cattle and soy price were obtained from IMAZON (Barreto *et al* 2008). In order to examine the changing relationship between price and deforestation over time, we calculated correlation coefficients between the time series using a moving nine year window, with



**Figure 2.** Relationship between change in deforested area during 2000–2006 and change in agricultural area (total crop harvested (cropland), pasture) in municipalities covered by more than 50% forest cover in the states of the Legal Amazon. Cropland plus pasture change against deforestation for (a) municipalities, with five outliers circled in blue; outliers were identified as those with absolute values of standardized residuals greater than two, and (b) excluding the five outliers. (c) Pasture versus deforestation, outliers excluded; (d) cropland versus deforestation, outliers excluded.

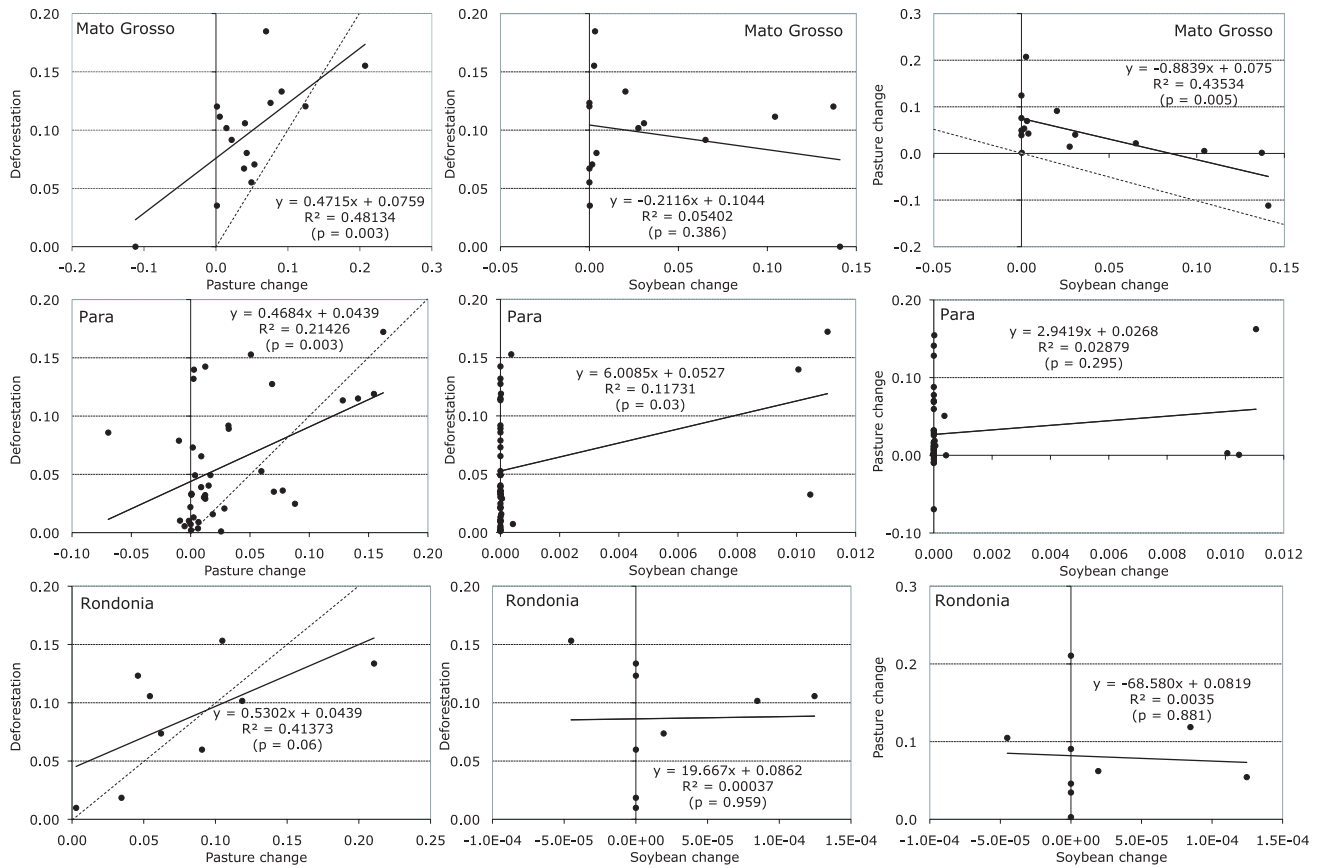
the price data leading deforestation by 1 year. The 9 year averaging period is a compromise between having enough data points within a window for calculating a correlation coefficient, but a small enough window so that there are enough correlation-coefficient calculations to show a trend in these over time. Also, since deforestation is not expected to respond immediately to price signals, we chose to use a 1 year lag, which is consistent with the way this data was provided by IMAZON, and also with other studies (Ewers *et al* 2008).

### 3. Results and discussion

The greatest amount of deforestation during the 2000–2006 period occurred in the states of Para, Mato Grosso and Rondônia (figure 1). Pasture area clearly decreased in the eastern and southern edges of the Legal Amazon (in Southeastern Mato Grosso, Tocantins, and eastern edge of Para), as well as in northern Amazonas, but increased in the interior Amazon (in Para, northwest Mato Grosso, and Rondônia). Total crop harvested area increased mainly in central Mato Grosso where soybean cultivation expanded, and decreased in the state of Para (mainly because of decline of crops other than soy). The pattern of deforestation therefore seems to be related to changes in pasture area in the interior Amazon, and to the changes in total harvested area of crops, driven by soybean expansion, in central Mato Grosso.

A simple linear regression analysis of deforested area during 2000–2006 against the change in agricultural area (total crop harvested area plus pasture), in municipalities with greater than 50% forest cover, reveals a weak relationship; however, when five municipalities that were outliers were removed a stronger relationship is revealed (figure 2)<sup>5</sup>. This relationship across the Legal Amazon constitutes good evidence for a relationship between deforestation and agricultural areas (areas under cropland/pasture). When we repeated the regression analysis with cropland or pasture alone as the independent variable, we found a strong relationship across the Legal Amazon between deforestation and change in pastures, but not with cropland. Multiple linear regression with both cropland

<sup>5</sup> Four of the five outliers (Paragominas, Cachoeira do Piria, Garrafo do Norte, and Abaetetuba) all lie in Para, and have much higher deforestation rates than change in agricultural area. The deforestation in these municipalities is related to the construction of highways and fires, and unrelated to agriculture. Manauquiri, in Amazonas, has much lower deforestation rates compared to agricultural expansion. Here the ratio of pasture (from census) to animal units in 2006 is much higher compared to its neighboring municipalities, suggesting that there may be an error in the data. Note also that Maranhão was excluded from the analysis because of several discrepancies observed in the deforestation data reported by PRODES between 2000 and 2006. For example, data for some municipalities in Maranhão indicated zero deforested area in 2000, but then in 2001 this figure abruptly rose to 100% deforested area. With little literature to support such rapid deforestation, a decision was made to remove these data from the analysis.



**Figure 3.** Relationship between deforestation, change in pasture area, and change in soybean area during 2000–2006 for municipalities covered by more than 50% forest cover, in three states of the Legal Amazon. The outliers identified in figure 2 are excluded here also.

and pasture as dependent variables revealed a statistically significant relationship for both variables (table 1).

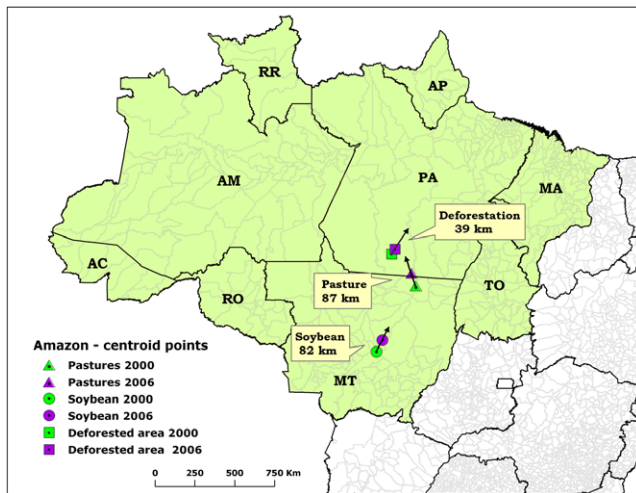
Next, we focused our analysis on the three Brazilian states with the greatest amount of deforestation—Mato Grosso, Rondônia, and Para—which together contributed to 84% of the total deforestation in the Legal Amazon in 2006. Simple linear regression between deforestation and changes in pasture and soybeans (figure 3), showed that deforestation is strongly related to pasture expansion in Mato Grosso ( $R^2 = 0.48$ ,  $p$ -value = 0.003) and Rondônia ( $R^2 = 0.41$ ,  $p$ -value = 0.06), and somewhat weakly related in Para ( $R^2 = 0.21$ ,  $p$ -value = 0.003). However, there is no statistical relationship between deforestation and soybean expansion in any of the three provinces. Multiple linear regression confirms these results (table 1), although it allows for soybeans to become weakly statistically significant in Mato Grosso and Para; however, as will be shown next, there is multicollinearity in the data, which prevents proper interpretation of these results. At first glance, this suggests that deforestation is mainly caused by pasture expansion, and not related to soybeans. However, there is a strong and statistically significant relationship between a decrease in pasture and an increase in soybean in Mato Grosso ( $R^2 = 0.44$ ,  $p$ -value = 0.005).<sup>6</sup> This suggests that soybean

is replacing pasture in Mato Grosso. It is possible that the increased pasture in Para and Rondônia (figure 1) is a result of the displacement of ranching from Mato Grosso, but this is only suggestive (we return to this point later).

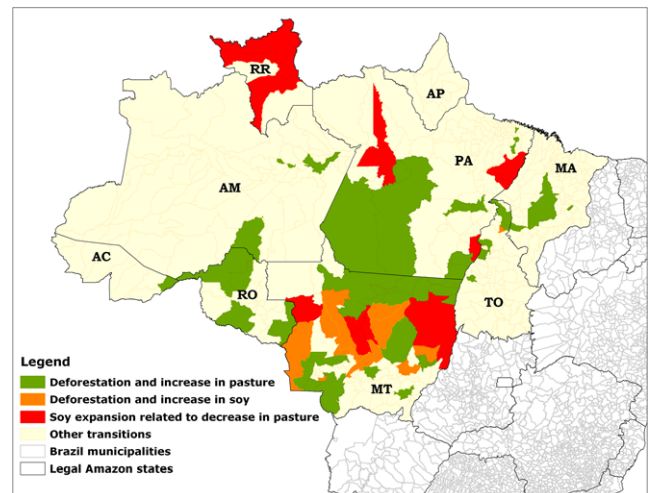
A centroid analysis of each land-use type for the Legal Amazon indicates that between 2000 and 2006, deforestation shifted 39 km to the northeast (figure 4). Pasture moved 87 km to the northwest from northeastern Mato Grosso to southwestern Para. Soybeans had an 82 km northeastward shift, from southern to northeastern Mato Grosso. Thus, the northward shift of soybean was accompanied by northward shift of both pasture and deforestation.

Finally, we examined the different transitions between land covers in the Legal Amazon (figure 5). Over most of the Legal Amazon, deforestation seems to be accompanied by a greater expansion of pasture than soy (except in Mato Grosso where a few municipalities have witnessed deforestation accompanied by greater soy expansion). Interestingly, there are also many municipalities in Mato Grosso where soybean expansion is accompanied by a decline in pasture area. This lends further support to the hypothesis that the decreases in pasture in Mato Grosso (see also figure 1) owing to soybean expansion may have been compensated by increases in pasture elsewhere in northern Mato Grosso, Para and Rondônia causing some deforestation indirectly, i.e., ‘displacement deforestation’.

<sup>6</sup> We examined the relationship between soybeans and pasture using all municipalities (and not just those with >50% forest). Our results were qualitatively similar to those presented here (supplementary figure 1 available at [stacks.iop.org/ERL/5/024002/mmedia](http://stacks.iop.org/ERL/5/024002/mmedia)).



**Figure 4.** Movement of the centroid of land-use types from 2000 to 2006. For each land use the centroid of all municipalities in the Legal Amazon, weighted by the land-use area in that particular year, was calculated.

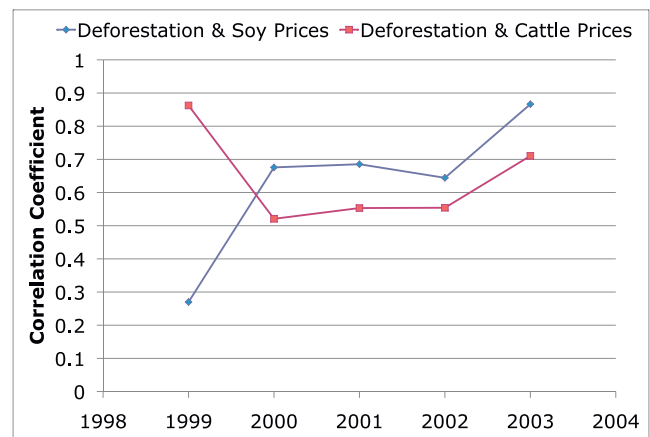


**Figure 5.** Land-use transitions between 2000 and 2006 in the Legal Amazon. In the municipalities where deforestation occurred over this period (green and orange), we separated those in which pasture increased from those where soy increased. (In municipalities where both soy and pasture increased, we labeled it using the dominant change.) Similarly, we identified municipalities where soy expanded while pasture decreased (and the decrease in pasture exceeds deforestation).

**Table 1.** Results from multiple linear regression of deforestation against cropland (or soybean) and pasture.

Coefficients	Estimate	Std error	t value	Pr(> t )
Legal Amazon (outliers excluded as detailed in the text)				
(Intercept)	0.018	0.003	5.578	<0.001
Cropland	0.618	0.110	5.620	<0.001
Pastures	0.754	0.062	12.197	<0.001
Residual standard error: 0.03292 on 140 degrees of freedom				
Adjusted R-squared: 0.5247, p-value: <math>2.2 \times 10^{-16}</math>				
Mato Grosso				
(Intercept)	0.056	0.016	3.535	0.004
Soybean	0.363	0.220	1.651	0.123
Pastures	0.651	0.164	3.960	0.002
Residual standard error: 0.03217 on 13 degrees of freedom				
Adjusted R-squared: 0.5053, p-value: 0.004066				
Para				
(Intercept)	0.041	0.008	5.171	<0.001
Soybean	4.768	2.473	1.928	0.062
Pastures	0.422	0.143	2.957	0.005
Residual standard error: 0.04269 on 37 degrees of freedom				
Adjusted R-squared: 0.2474, p-value: 0.001965				
Rondônia				
(Intercept)	0.043	0.026	1.610	0.159
Soybean	56.221	301.370	0.187	0.858
Pastures	0.533	0.257	2.071	0.084
Residual standard error: 0.04409 on 6 degrees of freedom				
Adjusted R-squared: 0.2228, p-value: 0.1980				

Our correlation analysis between price and deforestation adds further credence to our hypothesis (figure 6). The correlation between cattle prices and deforestation was 0.86 during the 1995–2003 period, but then dropped to be 0.5–0.6 before increasing again to 0.71 during 1999–2007. The correlation between soy prices and deforestation was 0.27



**Figure 6.** Correlation coefficient over time between the price of soy, price of cattle, and Amazon deforestation over the 1995–2007 period. Correlation coefficients are calculated over a moving 9 year window, with the price data leading deforestation by 1 year. Values are plotted at the center of each 9 year window (i.e., the first value indicated for 1999 is the correlation coefficient calculated over 1995–2003, while the last value for 2003 is the correlation coefficient over 1999–2007).

during 1995–2003, increased to between 0.6 and 0.7 in subsequent time periods, and reached 0.87 during 1999–2007.

#### 4. Conclusions

This study is not conclusive regarding the extent to which deforestation in the Legal Amazon is related to pasture expansion or soybean expansion because only statistical correlations were examined, which do not establish causation. However, the analysis of spatial patterns, as well as statistical



analysis allow us to draw the following general conclusions about the changes between 2000 and 2006.

The proximate cause of deforestation in the Legal Amazon was predominantly the expansion of pasture, and not of soybeans. However, in Mato Grosso, an increase in soybeans occurred in regions previously used for pasture, which may have displaced pastures further north into the forested areas, causing indirect deforestation there. Therefore, soybean cultivation may still be one of the major underlying causes of deforestation in the Legal Amazon.

Our results are consistent with previous studies that have suggested that recent deforestation in the Legal Amazon was predominantly due to cattle ranching (Morton *et al* 2006, Brown *et al* 2005, Greenpeace-Brazil 2009), and not soybean expansion. However, whereas these previous studies have used remote sensing imagery to analyze the subsequent land use following deforestation, we examined the large-scale relationship between deforestation and agricultural expansion, including potential geographic shifts in land use. Our results provide support for the hypothesis that soybean expansion in Mato Grosso may have replaced pastures, and displaced them further north into forest areas, causing deforestation indirectly.

There are other indirect pathways through which soybean could be leading to deforestation. For example, Fearnside (2005) suggests that while pasture occupies vast areas of land, soybean cultivation carries the political weight necessary to induce infrastructure improvements, which in turn stimulates crop expansion. Further, Nepstad *et al* (2006) suggest that growth of the Brazilian soy industry may have indirectly led to the expansion of the cattle herd. According to Nepstad *et al* (2006), soy has driven up land prices in the Amazon (5–10 fold in many areas of Mato Grosso), allowing many cattle ranchers to sell valuable holdings at enormous capital gains and purchase new land further north and expand their herd further. This hypothesis is consistent with our spatial analysis showing northward displacement of pasture, with declining pasture in parts of Mato Grosso, and increasing pasture further north (figures 1 and 4), and also supported by findings from other recent studies (Dros 2004, Cattaneo 2008). Our statistical analysis of the relationship between soy/cattle price and deforestation lends further credence to this hypothesis (figure 6). It shows that while the relationship between cattle price and deforestation has been more or less stable, soy has become increasingly related to deforestation over time. In summary, even if the *proximate* cause of deforestation was mainly ranching, it is likely that soy cultivation is a major *underlying* cause.

Our study findings have to be accompanied by some caveats. Data quality is an issue, especially with the annual IBGE statistics that are a result of expert surveys, rather than censuses. Further, by using harvested area to indicate cropland area, we have ignored multiple cropping; in doing so, we may have overstated the case for the influence of cropland expansion on deforestation, but this does not negate our general conclusions about the role of soy and pasture in deforestation. Also, in using livestock numbers to estimate

pasture area, we have assumed the absence of land-limited intensive livestock systems in the Amazon; however this seems to be a fair assumption (Carvalho 2006, Steinfeld *et al* 2006). Our analysis is also constrained by the available spatial data at the municipality level. We have accounted for the different municipality sizes by normalizing data by municipality areas in our regression analysis, and by weighting the centroid analysis by land-use areas in each municipality. A different configuration of municipalities would, however, likely lead to a different quantitative result. We believe, nevertheless, that our qualitative conclusions would not change.

Based on the challenges encountered in performing this study, we have the following recommendations. IBGE (and other statistical agencies) should provide their spatial database of municipalities along with a guide to their historical changes, including the specific changes for each municipality, the date of the change, and other relevant information. If INPE had provided their PRODES deforestation data spatially (or by municipality) prior to the year 2000, we could have expanded the study further back in time. Estimates of pasture area were not available annually, we had to estimate it based on data on the number of animals. Given the importance of ranching in the region, it would be useful to have annual estimates, either based on remote sensing, or sample surveys. More research on the relationship between results acquired from satellites and those from censuses and surveys would help this type of study in the future. Currently, our deforestation data is from remote sensing, while our agricultural area data are based on censuses and surveys. A more robust analysis would be possible if all data were consistently available from a single source.

These findings point to the need for more large-scale studies, and more field-based research to test the land-use displacement hypothesis. Policy makers face important tradeoffs to satisfy the demands of the livestock and soybean industries versus conservation of the Amazon, and policies that benefit one group will likely work to the detriment of the others. The soy industry is expanding rapidly in Brazil, supported by the notion that they are not causing new deforestation; the blame continues to be placed on cattle ranching. However, as this research and other studies have shown, the dynamics of land-use change is complex, and simple-minded policies to curb deforestation, without a full understanding of the underlying dynamics, will not work.

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