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# Statistical confirmation of indirect land use change in the Brazilian Amazon

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## Abstract

Expansion of global demand for soy products and biofuel poses threats to food security and the environment. One environmental impact that has raised serious concerns is loss of Amazonian forest through indirect land use change (ILUC), whereby mechanized agriculture encroaches on existing pastures, displacing them to the frontier. This phenomenon has been hypothesized by many researchers and projected on the basis of simulation for the Amazonian forests of Brazil. It has not yet been measured statistically, owing to conceptual difficulties in linking distal land cover drivers to the point of impact. The present article overcomes this impasse with a spatial regression model capable of linking the expansion of mechanized agriculture in settled agricultural areas to pasture conversions on distant, forest frontiers. In an application for a recent period (2003–2008), the model demonstrates that ILUC is significant and of considerable magnitude. Specifically, a 10% reduction of soy in old pasture areas would have decreased deforestation by as much as 40% in heavily forested counties of the Brazilian Amazon. Evidently, the voluntary moratorium on primary forest conversions by Brazilian soy farmers has failed to stop the deforestation effects of expanding soy production. Thus, environmental policy in Brazil must pay attention to ILUC, which can complicate efforts to achieve its REDD targets.

**Keywords:** soy, cattle, deforestation, Amazonia, biofuel

## 1. Introduction

Brazil's commitment in 2008 to reduce deforestation in the interest of the UN's Reducing Emissions from Deforestation and Forest Degradation (REDD) program has raised hopes for a new era of sustainable relations between coupled natural and human systems in Amazonia (Nepstad *et al* 2009). Nevertheless, deforestation continues here, with the expansion of pastures for cattle ranching accounting for the lion's share of forest loss (Naylor *et al* 2005, Margulis 2004, Walker *et al* 2009a). Recently, some have called attention to the

impacts of soy production, and direct encroachments of soy fields into the Amazonian forest have been observed (Brown *et al* 2005, Morton *et al* 2006, Hecht and Mann 2008, Walker *et al* 2009b). The present research letter considers the threat posed by soy, and mechanized agriculture more generally, which arises by virtue of indirect land use change, or ILUC. ILUC takes place when agricultural activities displaced from one region are reconstituted in another one (Searchinger *et al* 2008, Lapola *et al* 2010). In such a situation, deforestation at particular locations occurs partly due to events far away, a circumstance that complicates measurement. This letter uses spatial regression modeling to provide the first statistical

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assessment of ILUC for the Brazilian Amazon (LeSage and Pace 2009). Our results show to what extent forest loss in humid regions of the Brazilian Amazon is linked to expanding soy production in the transitional forests and cerrado regions of its southern and eastern rims. The results point to the need for (1) linking land use policies across agricultural sectors, for (2) the inclusion of ILUC in measuring the carbon 'footprint' of soy crops, whether produced for biofuels or other end-uses, and for (3) vigilance in ensuring the integrity of Brazil's system of protected areas.

## 2. Indirect land use change and pasture displacement

Global demands for food and biofuel are expected to soar in coming decades (USDA 2007, USDA 2010, Delgado *et al* 1999, FAO 2009). To meet these demands, new land will need to be brought into production. Brazil, with its abundant land resource, will no doubt continue to play an important role as a global supplier of agricultural commodities (Pingali *et al* 2008, Borlaug 2008). Since 1990, the Amazonian cattle population has grown from 25 million to more than 70 million, and the area of soy, from 16 000 km<sup>2</sup> to more than 60 000 km<sup>2</sup> (IBGE 2010). Production growth has come with cost and the loss of over 700 000 km<sup>2</sup> of forest. Although conversions of forest to mechanized agriculture have been observed (Brown *et al* 2005, Morton *et al* 2006), pasture expansion remains by far the primary direct cause of Amazonian deforestation. Recent research suggests, however, that mechanized agriculture may exert a significant indirect effect, by the displacement of old pastures, and their recovery on the forest frontier (Lapola *et al* 2010, Barona *et al* 2010). The present letter takes this displacement mechanism as ILUC, for the purposes of its analysis (Lapola *et al* 2010, Richards 2011, Walker 2011).

ILUC occurs as loss of land dedicated to a given crop (or production strategy) in one region triggers its expansion in another region. For example, as fuel crops displace food crops in the American Midwest, lands dedicated to food production emerge elsewhere, possibly the Amazon Basin (Searchinger *et al* 2008). Estimates of ILUC have largely been conducted at global scale, using general equilibrium models to quantify the effect. This paper takes a regional approach, and develops its statistical model in view of the spatial mechanisms at work impacting the production of the commodities in question, in this case primarily beef and soy. In particular, as rents for relatively intensive soy production rise, pastures are converted to soy fields. Given that the demand for beef remains strong, new pastures emerge elsewhere, for example at the expense of forest, in order to avoid supply shortfalls. This process, also referred to as land use displacement (Barona *et al* 2010, Richards 2011), implies that the more extensive activity, ranching, is displaced to where land can be reacquired at a low cost. Thus, Amazonian deforestation results from a land use cascade, from zones of mechanized crop production to the forest frontier (Walker *et al* 2009a, Lambin and Meyfroidt 2010). The phenomenon of ILUC brings into question Brazil's 'Soy Moratorium', an agroindustry-led initiative to limit deforestation by stopping direct encroachments of soy fields into closed moist forest (ABIOVE 2010).

The measurement of ILUC has proved challenging, given the spatial displacement of causality (Babcock 2009a, 2009b). Globally oriented studies generally recognize that ILUC effects emerge at distance from the point of origin, but they stop after identifying Brazil as a point of impact for food production dynamics in the United States (Fargione *et al* 2008, Searchinger *et al* 2008). The present letter does not address global or international ILUC, but examines the process as it manifests in the Brazilian Amazon. Recently, simulation modeling based on global demand projections estimated that nearly 60% of Amazonian deforestation occurring between 2003 and 2020 will be attributable to ILUC associated with biofuel production (Lapola *et al* 2010). Further, statistical analysis has been highly suggestive of a northward displacement of cattle by soy production (Barona *et al* 2010). This letter provides a complement to such studies by capitalizing on advances in GIS technology and recent innovations in spatial statistics. Whereas the research to date has projected demands to predict future deforestation magnitudes or examined land uses for correlation with nearby land covers, we implement a new statistical methodology capable of linking frontier deforestation to distal events, such as the expansion of soy production in a settled agricultural area.

## 3. Methods

In general, statistical explanations of land cover change have defined explanatory and dependent variables for a single location, possible with a set of nearby neighborhoods, a method that does not capture the effect of potentially distant influences (e.g., Pfaff 1999, Andersen *et al* 2002, Chomitz and Thomas 2003, Caviglia-Harris 2004). The approach in this letter overcomes the problem of distal spatial effects by using GIS to associate locations in the forest frontier where deforestation is occurring with 'distant' neighbors in the settled agricultural parts of Amazonia. The statistical models implemented possess a sufficiently general form that they can be implemented wherever ILUC is of interest to policy makers.

The statistical analyses are conducted at the level of the municipio, roughly equivalent to a US county; the estimation data set includes yearly information from 2001 to 2008 for deforestation, changes in areas dedicated to soy, changes in cattle population, rainfall levels, and farm gate prices for beef. Statistical methods implemented include a standard ordinary least squares regression with pooled data (OLS), and two panel analyses using dummy variables for the years in question and allowing for fixed effects to control for unobserved municipal variables remaining constant over time. The two panel analyses differ in their inclusion (FE2) or not (FE1) of a lagged soy variable. All models account for local spatial autocorrelation for the cattle population variable, given agricultural decision making is often contagious. After first differences were calculated [ $t - (t - 1)$ ], results span the period 2002–2008. In the OLS and FE2 models, the results were reduced by an additional year (2002) given the inclusion of the lag variable. Consequently, the results presented in these models are for the period 2003–2008.

The prime innovation in this analysis is the treatment of the impact of soy expansion on distant deforestation. To

accomplish this, the Legal Amazon was partitioned spatially into a time-dependent ‘forest frontier’ and ‘agricultural area’ (south and east). Since agricultural development is a dynamic process, agricultural areas and forest frontiers are inherently in flux. With the partitions defined, spatial weights matrices were developed, linking municipalities in the forest frontiers to municipalities in the agricultural areas, with strength of linkage defined by distance between paired municipalities. The spatial weights matrices were then used to create independent variables capturing soy expansion in distal municipalities as a function of ‘nearness’ to the observations in the forest frontier, for which deforestation was estimated. These independent variables were used in conjunction with others to provide the analysis data set. Using spatially weighted independent variables results in a so-called spatial Durbin model, or SDM (LeSage and Pace 2009). The novelty of the SDM of the present letter is its reliance on a matrix linking points of impact to distal, independent variables. The data used are described in the appendix, as is the approach to defining the spatial matrices.

We estimated deforestation rates  $R$  for a municipality  $e$  in the extensive frontier in year  $t$  ( $R_{e,t}$ ) as follows:

$$R_{e,t} = c_e + \gamma_t + \alpha W_{1e,t} \Delta S_t^i + \varphi W_{2e,t} \Delta C_t + X_{e,t} \beta + \varepsilon_{e,t}. \quad (1)$$

This is a two-way effects model where  $c_e$  is the so-called fixed effect,  $\gamma$  is the time-specific effect, and  $\varepsilon$  is the idiosyncratic error. The  $W$ s are the spatial weight matrices defined in the appendix.  $\Delta S_t^i$  is a  $(N \times 1)$  vector of first differences in the area planted with soybeans ( $S$ ) in the agricultural municipios or  $\Delta S_t^i = S_t^i - S_{t-1}^i$ , and  $\Delta C_t$  is a  $(5 \times 1)$  vector of first differences in cattle herd ( $C$ ) in the closest five frontier municipios to  $e$  or  $\Delta C_t^i = C_t^i - C_{t-1}^i$ . The  $X_{e,t}$  vector contains other control variables such as rainfall levels, and farmgate prices of beef. Parameters to be estimated are  $\alpha$ ,  $\varphi$ , and  $\beta$ . The model was estimated using a within estimator (i.e. fixed effects) with time dummies, which controls for unobserved time-constant variables at municipality level such as soil type (Cameron and Trivedi 2005). Fixed effects estimation with unbalanced panels, which is our case, requires stronger assumptions than if the panel were balanced. The key assumption to obtain consistent estimators is that the factors affecting attrition (i.e. municipios dropping out of frontier set), must be uncorrelated with unobserved factors in  $\varepsilon_{e,t}$  (Wooldridge 2002). The full regression results of this analysis are shown in the appendix.

## 4. Results

The statistical models, undertaken for a six year period (2003–2008) and based on 761 municipalities (municipios) in the Legal Amazon of Brazil, indicate that deforestation in the forest frontiers of the basin is strongly related to soy expansion in its settled agricultural areas, to the south and east (see table A.1). Figure 1 shows the geographic center for these twinned partitions in 2001 and 2008, which demonstrate a movement of production northwest. ILUC as measured by the analysis is substantial for the Amazon (figure 2). Results in terms of average elasticities are 0.6% (regression: ordinary least squares, OLS), 1.2% (regression: fixed effects without

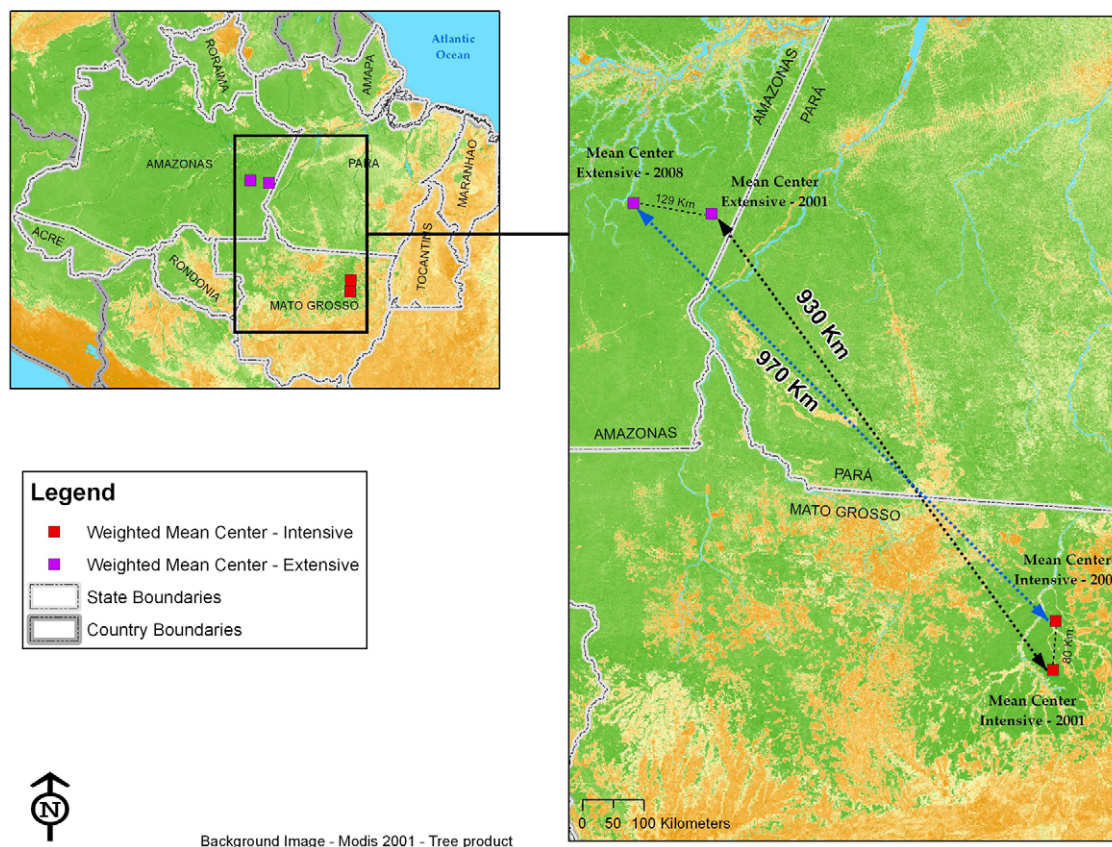
time lag for soy, FE1), and 4% (regression: fixed effects with time lag for soy, FE2). For the FE2 model, this means that a 1% reduction in soy field expansion in the settled agricultural area yields a 4% decrease in frontier deforestation. These results can be translated into absolute measures as follows. Between 2003 and 2008, soy expanded by 39 100 km<sup>2</sup> in basin agricultural areas, mostly in Mato Grosso. A drop in this amount by 10% (3 910 km<sup>2</sup>) would have led to a reduction in deforestation of 4061 km<sup>2</sup> by the OLS model, 10 963 km<sup>2</sup> by the FE1 model, and 26 039 km<sup>2</sup> by the FE2 model (figure 2). The measured ILUC impact is greater for the fixed effects, panel estimations, preferred in the present setting given their ability to control for unobserved and unmeasured time-constant deforestation drivers. Such control is quite powerful, and eliminates the need for explicitly including variables that do not change over the times period, such as market accessibility associated with the road system, soils, and so on. The largest ILUC effect is observed with the FE2 model, which allows time lags in the impact of distant soy expansion, a reasonable assumption given that relocation to frontier areas may take longer to occur. The findings reveal substantial impact, amplified in magnitude beyond a one-to-one replacement of new for old pastures, probably resulting from the disproportionate appreciation of land in soy regions in comparison to the frontier.

## 5. Discussion and conclusions

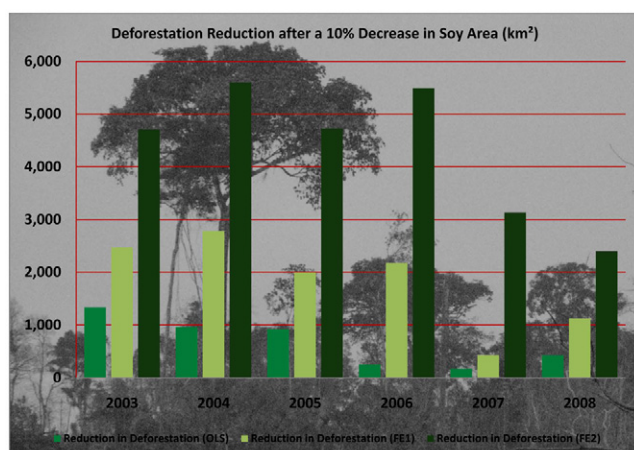
The indirect impacts of soy production in the Brazilian Amazon, though often referred to anecdotally, have remained obscure given the conceptual obstacles that deter an estimation of the role and impact of spatially distal effects. The present letter surmounts this longstanding obstacle by incorporating a ‘neighborhood’ of potentially distant political units. This conceptual innovation is essential to capture indirect effects in the Amazon Basin, where the displacement of cattle production due to agricultural expansion drives land use change in counties located hundreds of kilometers away. The results suggest that Amazonian ILUC is not only measurable but that the impact is significant.

Consequently, increased mechanized crop production must be viewed as a driver of Amazonian deforestation, even if new fields replace only existing pastures or savannah lands at the periphery of the humid portions of the basin. The results thus call into question the effectiveness of the soy moratorium in reducing deforestation, and suggest that environmental policy in Brazil must recognize land use linkages in the agricultural sector of the economy. The results also suggest that supply chains crossing international boundaries may stimulate Amazonian deforestation via ILUC. That is, as global demands for Brazilian agricultural commodities grow, Amazonian deforestation may result by virtue of the process identified in this letter. Consequently, global efforts to reduce greenhouse gas emissions by substituting biofuels for petroleum products must proceed with care, in order not to intensify processes of Amazonian deforestation via ILUC, thereby undermining Brazil’s REDD objectives.





**Figure 1.** Advancement of the ‘Intensive’ and ‘Extensive’ frontiers in the Legal Amazon between 2001 and 2008. The mean center of more intensive agricultural production has advanced northward 80 km; the mean center of ‘extensive’ cattle production moved northwest approximately 130 km. In both years, the extensive and intensive frontiers’ centers were distant by more than 900 km.



**Figure 2.** Deforestation reduction after a simulated 10% decrease in the expansion of soy production 2003–2008.

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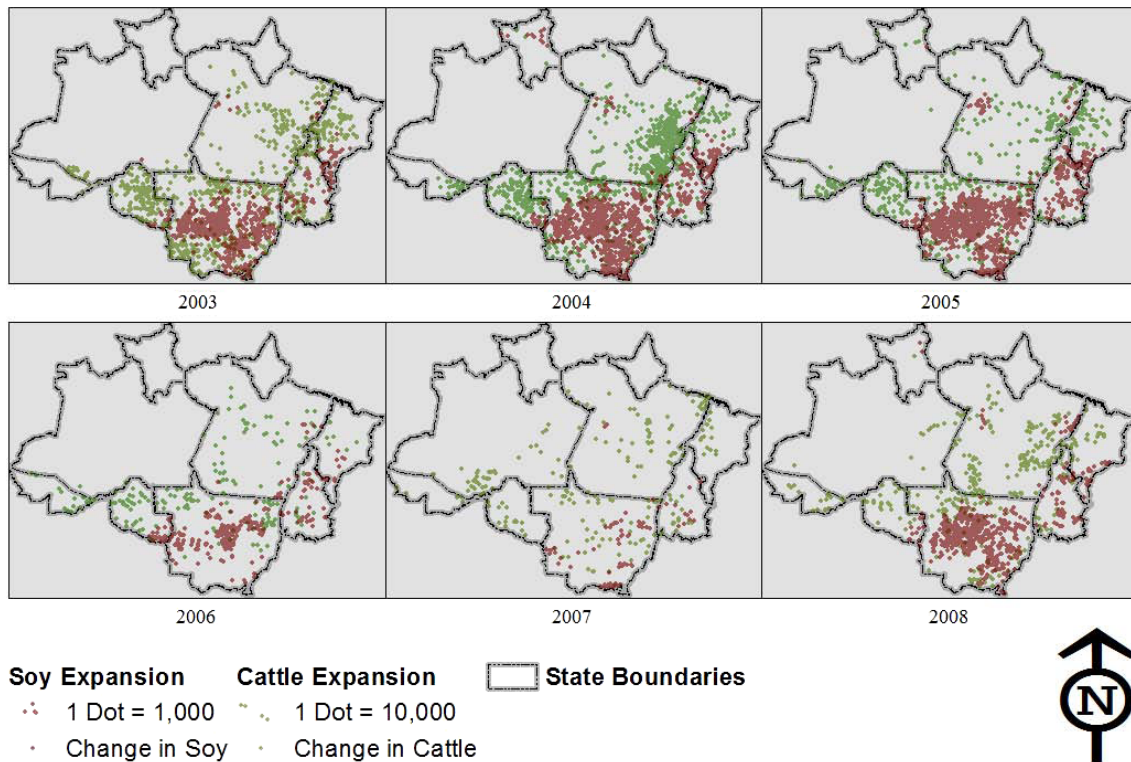
NASA NNX07AF16G (Biodiversity implications of forest disturbance and related landscape dynamics in the Brazilian Amazon). However, the views expressed are ours alone, and do not necessarily reflect those of the National Science Foundation or NASA. We would like to thank the anonymous reviewers of the journal, whose comments improved the text. Nevertheless, we remain fully responsible for any errors that might remain.

## Appendix

### Data

(1) *Forest loss*,  $Re_{i,t}$ . The dependent variable  $Re_{i,t}$ , the annual deforested area in  $\text{km}^2$  in municipality  $i$  in year  $t$ , was obtained from INPE’s PRODES Digital website (INPE 2010). A control variable named ‘Notobsv’, which is the area not classified by satellites in each municipality (Notobsv) owing to cloud cover and other problems such as lack of imagery, was also included.

(2) *Soy area*,  $\Delta S_t$ . The independent variable of interest, namely changes in area of soy planted, was obtained at the municipal level for the period in question from the Instituto Brasileiro de Geografia e Estatística’s (Brazilian Institute of Geography and Statistics) Produção Agrícola Municipal (municipal level agricultural production). The database was



**Figure A.1.** Annual expansion of cattle and soy production in the Legal Amazon 2003–2008. Red dots represent a 1000 ha increase in soy production  $t - (t - 1)$ . Green dots represent an increase in 10 000 head of cattle  $t - (t - 1)$ . Growth in both cattle and soy was particularly strong from 2003 to 2004, when export conditions were highly favorable, given high prices for both products and the low exchange rate between the Brazilian Real and the US \$.

accessed online through the Sistema IBGE de Recuperação Automática (Automatic Recuperation System IBGE, SIDRA). Changes in soy area were calculated as  $[t - (t - 1)]$ .

(3) *Cattle population,  $\Delta S_t$ .* Cattle populations were used to define the município classifications. Cattle population data were obtained from IBGE through the database Pesquisa Pecuária Municipal (municipal level cattle research) and downloaded through SIDRA. Changes in cattle populations were calculated as  $[t - (t - 1)]$ . Changes in cattle and soy for the period 2003–2008 are included in figure A.1.

(4) *Precipitation, in vector  $X_{e,t}$ .* Precipitation can negatively impact deforestation rates because high rainfall levels may hamper machinery operations used to bring trees down in addition to slowing the burning of the fallen biomass. We used precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM), monthly product 3B43, downloaded from NASA's ftp site disc2.nascom.nasa.gov. The monthly 0.25° resolution precipitation rasters from 2001 to 2008 were converted to annual precipitation using GIS raster algebra operations. We then extracted the precipitation values at the municipality seats using a point vector GIS file and used those values in the regression analysis. We opted to use the precipitation values at the seat rather than the average within the municipality because certain municipalities are very large but deforestation tends to concentrate around the municipality seat. Thus, the average would not represent the relevant precipitation information.

(5) *Farm gate prices for beef, in vector  $X_{e,t}$ .* Farmgate prices of beef (in Reais \$/ton) were used as proxies for land rents at the municipality seat. We obtained prices of beef through field interviews conducted in 2000, 2005 and 2007 (Arima et al 2006, Walker et al 2009a) and from published agricultural almanacs (AnualPec 2003, 2009) for 42 municipalities. We calculated the farmgate price ( $P$ ) at any other given municipality seat  $i$  as the price  $M$  paid at the known locations  $j$  (e.g. municipalities with meat packing plants and slaughterhouses) minus the costs of transportation (CT) from  $i$  to  $j$ . Or,  $P_i = \text{Max}(M_j - \text{CT}_{ij} : j = 1, \dots, 42)$ . Transportation costs between  $i$  and  $j$  were calculated within ArcGIS using least cost distance functions. We assigned a friction value, which represents the costs of traversing the raster cell, according to the mode of transportation and quality and type of infrastructure (Arima et al 2007).

(6) *Protected area.* The amount of protected area in each municipality, which is a key variable to explain deforestation (Walker et al 2009c), though variable through time, showed little variation in most extensive municipalities in the period 2001–2008. Thus, this variable was regarded as time-constant and was controlled for in our fixed effect estimation procedure.

#### Definition of the matrices

The analysis required the partitioning of the Legal Amazon into areas from which net ILUC was exerted and into which the effect was exhibited. The first step therefore was to define sets



**Table A.1.** Regression results of indirect land use change analysis. (Note: significance levels are two-tailed probabilities.)

Variables	Coefficients (robust st. error)		
	FE1	FE2	OLS
$W_1 \Delta S$	0.0069 <sup>a</sup> (0.0012)	0.0126 <sup>a</sup> (0.003311)	0.0055 <sup>b</sup> (0.0033)
$W_{1,-1} \Delta S_{-1}$ (one lag)		0.0112 <sup>a</sup> (0.0024)	-0.0011 (0.0026)
$W_2 \Delta C$	0.0003 <sup>c</sup> (0.0001)	0.0002 (0.0002)	0.0025 <sup>a</sup> (0.0004)
Rainfall (mm year <sup>-1</sup> )	-0.0058 <sup>b</sup> (0.0030)	-0.0173 <sup>a</sup> (0.0064)	0.0116 <sup>a</sup> (0.0026)
Fgbf <sub>-1</sub> (one lag)	-0.0083 (0.0172)	-0.0514 (0.0378)	-0.0295 <sup>a</sup> (0.0071)
Notobsv	-0.0147 <sup>b</sup> (0.0076)	-0.0094 (0.0067)	-0.0041 <sup>a</sup> (0.0011)
2003	18.1081 <sup>a</sup> (4.9460)	-86.6633 <sup>a</sup> (17.8447)	0.5031 (10.9265)
2004	17.3043 <sup>c</sup> (7.7189)	-54.2192 <sup>a</sup> (9.3054)	-4.2910 (9.3242)
2005	17.5262 <sup>c</sup> (7.7189)	-49.4495 <sup>a</sup> (9.3054)	12.8247 (9.3242)
2006	22.4225 <sup>a</sup> (8.4964)	-32.1136 <sup>c</sup> (14.3268)	15.2490 (15.1281)
2007	26.8511 <sup>a</sup> (8.3285)	2.2219 (14.5758)	14.9001 (11.5375)
2008	13.8836 (10.1159)	—	—
Constant	-3.7351 (20.0873)	41.5097 (60.2117)	-4.2721 (17.2459)
$\sigma_c$ (sd of individual effect)	68.25	78.36	—
$\sigma_e$ (sd of idiosyncratic error)	41.23	43.04	—
Number of pooled obs.	3228	1907	1907
Number of groups (frontier munic.)	738	640	640

<sup>a</sup> Significant at 0.01 level. <sup>b</sup> Significant at 0.1 level. <sup>c</sup> Significant at 0.05 level.

of municipios  $E = \{e : e = 1, \dots, M \text{ is a frontier municipio}\}$  and  $I = \{i : i = 1, \dots, N \text{ is an agricultural municipio}\}$  in the Legal Amazon for year  $t$ . Classifications were then based on the relative growth in cattle and soy areas for  $t$ . Where neither cattle nor soy expanded, or where both were negative, the municipios were classified as non-frontiers and were excluded from the calculation of the spatial matrices for year  $t$ .

Two spatial matrices were then created for inclusion in the models. The first spatial weights matrix  $W_1 (M \times N)$  was created to account for the so-called indirect effect, whereby changes in land use, specifically the expansion of soy in a settled agricultural area, are linked to distant changes in, deforestation in forest frontiers. Thus, we link change in the amount of soybean area planted in the agricultural municipio  $i$  for year  $t$  to frontier municipio  $e$ . This matrix was defined as a function of distances from each frontier municipio  $e$  to all agricultural municipios  $i \in I$ . Define  $D_{ei} = [d_{e1}, d_{e2}, \dots, d_{ei}]$  where  $d$  is the Euclidean distance from municipality  $e$  to  $i = 1, \dots, N$ . Define a constant  $h = \max(D_{ei}) + \min(D_{ei})$  where min, max are the smallest and largest distances calculated in

$D$ . The weight matrix was then calculated as  $W_{1ei} = [h - d_{e1}, h - d_{e2}, \dots, h - d_{ei}][Nh - \sum_{i=1}^N d_{ei}]^{-1}$ , where the last term is a scalar used to normalize the vector of weights to one. This operation inverted the distance-based values, assigning larger weights for municipalities that are the closest (small distance).

A second spatial matrix  $W_2 (M \times 5)$  was included to capture local spillover effects of changes in cattle herds in the five nearest neighboring extensive municipios of  $e$ . Once the five nearest neighbors were identified, then this second matrix was simply set to  $W_{2e,t} = [0.2 \ 0.2 \ 0.2 \ 0.2 \ 0.2]$ . This improves consistency of the estimations because it controls for unobservables that are likely to affect cattle expansion and therefore deforestation.

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