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Abstract

Protected areas are increasingly used as a tool to fight against deforestation. This paper presents new evidence on the spillover effects that occur in the decision to deforest and the creation of protected areas in local administrative entities in Brazilian Legal Amazon over the 2001-2011 period. We also highlight the interdependence between these two decisions. We proceed in two steps. First, we assumed that protected areas are created to stop the negative effects of deforestation on biodiversity. In order to control for the non-random location of protected areas, biodiversity indicators are used as excluded instruments. This model is estimated using a spatial model with instrumental variables. Second, a simultaneous system of spatially interrelated cross sectional equations is used to take into account the interdependence between the decision to deforest and the creation of protected areas. Our results show (i) that deforestation activities of neighboring municipalities are complements and that (ii) there is evidence of leakage in the sense that protected areas may shift deforestation to neighboring municipalities. The net effect of protected areas on deforestation remains however negative; it is moreover stable across two sub-periods. Our results confirm the important role of protected areas to curb deforestation and thereby biodiversity erosion. Moreover, they show that strategic interactions deserve attention in the effectiveness of conservation policies.

Keywords: Protected areas; deforestation; spatial interactions; simultaneous equations; Brazil; Amazon.

Code JEL: Q23, Q57, C31.

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1 Introduction

The process of deforestation in the tropics has been the subject of an extensive literature (Angelsen & Kaimowitz 1999; Barbier 2004; and Geist & Lambin 2002, among others). Though substantial forested areas were converted into agricultural land in historical times and therefore contributed to population and income increases, contemporary deforestation generates concerns, since it is now admitted that deforestation activities have negative effects on the environment. For instance, forests are major carbon sinks, second only to oceans,[1] therefore contributing to mitigating climate change. They are also home to numerous known and unknown species. Habitat disappearance in the tropics is a major concern, since the biodiversity gradient is greater in tropical than in cooler regions. Human encroachment is likely to drive species to extinction (Laurance et al. 2012). Moreover, land use changes, which are mainly the result of deforestation, contributes to anthropogenic GHG emissions. Van der Werf et al. (2009) concludes that deforestation is the second CO2 emitter after fossil fuel combustion. Finally, forests contribute to the water cycle: the Amazon basin accounts for one fifth of the total freshwater drained into oceans.

According to the Brazilian National Institute for Space Research (INPE), the year 2009 marked a reference point with respect to deforestation in Brazil: "only" 750,000 hectares were depleted, an impressive 75% decrease with respect to the 2.8 million hectares peak in 2004. Several voices, including Nepstad et al. (2009), do not exclude that the 2008-2009 financial crisis has something to do with this phenomenon. One may question this statement by considering the efforts made in the literature to unravel causes of deforestation in that region (see Andersen et al. 2002; Araujo et al. 2009; Binswanger 1991; Cattaneo & San 2005; and Pfaff 1999 among others). Moreover, Brazil is thoroughly engaged in environmental policies and the number of protected areas located in the Brazilian Legal Amazon has been substantially rising.[2] Protected area surfaces in the Brazilian Legal Amazon have doubled between 2000 and 2009 and amount today to 2 million square kilometers, representing 42%

[1] According to IPCC, it is, however, likely the case that CO2 uptake from the atmosphere by oceans will decrease (IPCC 2007, paragr.7.3.4.2), thus reinforcing the role of forests as carbon sinks.

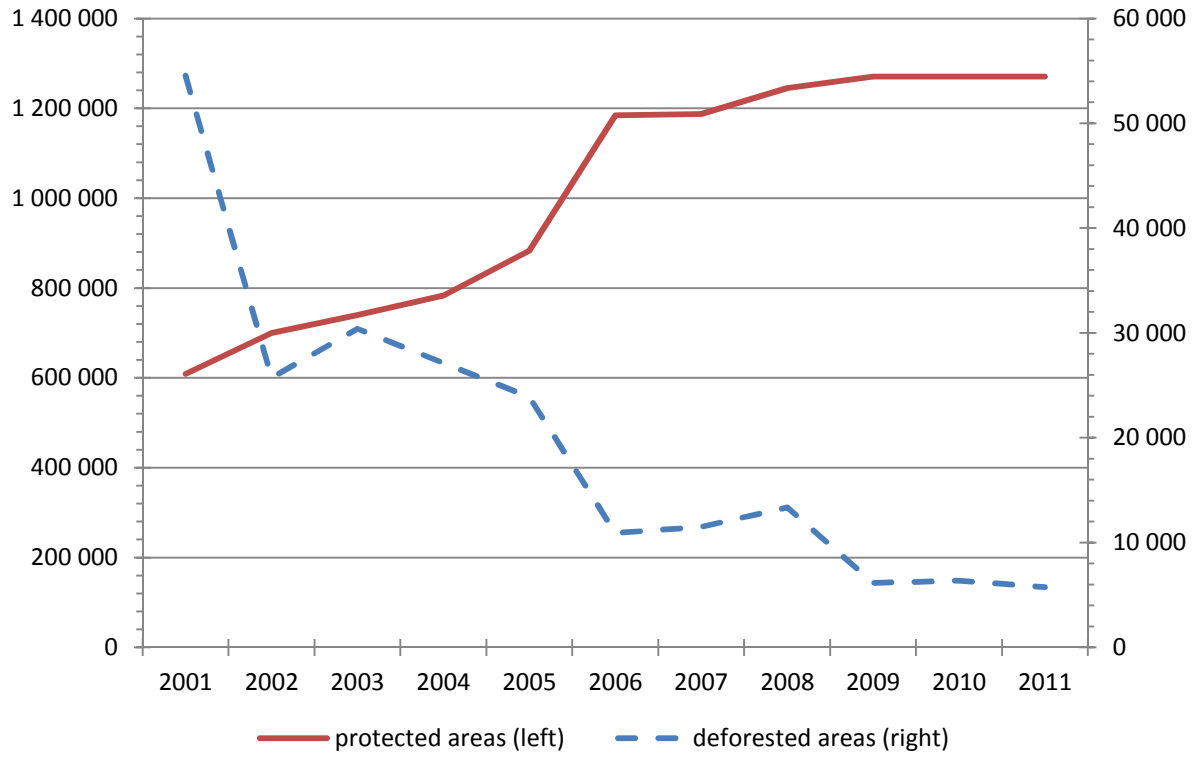
[2] The Brazilian Legal Amazon is a 5 million square kilometer administrative area defined for regional planning purposes comprising 4 million square km of tropical forests as well as the savanna (cerradão), and transitional vegetation in the southeast areas of the region. It covers nine states out of the twenty-nine of the Brazilian federation: Acre, Amapa, Amazonas, Mato Grosso, Rondonia, Roraima, Tocantins, Para, and a part of Maranao state.

of the surface in the Brazilian Amazon. Figure 1 below evidences a negative correlation between protected and deforested areas. Brazil is thus an illustrative example of conservation policies in developing countries which have often mainly relied on the implementation of protected areas (see e. g. the thorough review of Palmer & Di Falco (2012)).

The effective impact of protected areas on deforestation is subject to debate (Gaston et al. 2008; and Gaveau et al. 2009). Several authors focus on biases in the spatial distribution of protected areas: protected areas are not randomly distributed and are rather located on land of which characteristics do not favour agricultural expansion owing to their low soil fertility, slopes, poor accessibility, etc. (Albers & Ferraro 2006). Neglecting this bias could induce an overestimation of the impact of protected areas on deforestation (Nepstad et al. 2006; Sánchez-Azofeifa et al. 2003). Several empirical studies tackle this potential bias using matching methods (Andam et al. 2008; Gaveau et al. 2009; Pfaff et al. 2009; and Pfaff et al. 2014) which consist of selecting for every protected area (i.e. “treated area”) a control area with similar observable characteristics. However, the main limitation of this method is that the treated and the non-treated areas may differ in unobservable characteristics. Moreover, protected areas could cause leakages in deforestation (Ewers & A. S. L. Rodrigues 2008).

In this paper, we intend to add to the literature dedicated to the effectiveness of protected areas on deforestation using municipal level data over the Brazilian Legal Amazon. First, we take into account the non-random distribution of protected areas, using an instrumental variable method. More precisely, we follow Cropper et al. (2001), who uses a bivariate probit and Sims (2010) who uses the method of instrumental variables. Our identification strategy relies on the assumption that the creation of a protected object is not only for the purpose of reducing deforestation but also to preserve biodiversity. Consequently, an originality of this paper is the use of indicators of biodiversity, which could encourage Brazilian municipalities to establish protected areas, as instrumental variables. Second, we focus on the issue of leakages i.e. whether protected areas induce shifts in deforestation, as a result of spatial dependence in decisions regarding the establishment of protected areas, as well as land clearing decisions.

Figure 1. Evolution of protected areas and deforestation in the Brazilian Legal Amazon, square kilometers



Source : INPE, authors' calculations. Note that protected areas are from federal and state entities but indigenous lands are not included.

2 Literature review

Existing empirical studies have mainly focused on the determinants of deforestation. The main determinants discussed are the expansion of agricultural crops, roads, socioeconomic characteristics, spatial interactions, and protected areas (Andersen et al. 2002; Andrade de Sá et al. 2013; Araujo et al. 2009; Barona et al. 2010; Mertens et al. 2002; Chomitz & Thomas 2003; Pfaff 1999; Walker et al. 2000; Pfaff et al., 2009; Mendonça et al. 2012).

2.1 The determinants of deforestation

Agricultural expansion is the main driver of deforestation in the Amazon (Chomitz & Thomas 2003). According to these authors, deforestation is favored by the high agricultural potential of the area. Thus, if the opportunity cost of agricultural activities is higher than other land uses, the propensity to clearing the forest will be important. This phenomenon may be enhanced by breeding. Indeed, intensive livestock operations require a large area for

the production of animal feed. Road construction, in turn, reduces the opportunity costs of agricultural production by bringing forest areas suitable for agriculture closer to the nearest market (Walker et al. 2000; Andrade de Sá et al. 2013). However, the overestimation of the impact of roads is possible, since some political leaders have constructed them in areas not suitable for agricultural activities. One way to minimize this bias is then to control for the effect of roads by soil fertility.

Socioeconomic characteristics, especially income and consumption, are the main explanatory factors of deforestation. They positively influence it when it falls below a certain threshold. According to the environmental Kuznets curve hypothesis, during the takeoff phase of accelerated growth, they increase very quickly with, in addition, high environmental degradation; however, once a certain threshold is reached, the preferences of populations become favorable to environmentally friendly goods and services, which leads to a reduction in environmental degradation. Thus, after a certain level of development income will have a negative effect on deforestation. There is thought to be, therefore, a non-linear, inverted U-shaped relationship between deforestation and long-term income. This hypothesis was tested in several studies, but the results are contradictory (Barbier & Burgess 1997; Dinda 2004; Culas 2012; and Choumert et al. 2013).

Finally, several econometric studies (Aguiar et al. 2007; Corrêa de Oliveira & Simões de Almeida 2010; and Igliori 2006) have addressed the issue of spatial interactions in the Legal Amazon. These studies highlight the presence of a positive correlation between deforestation within a locality, and that which takes place in its vicinity. In Costa Rica and Sumatra, other studies tested the displacement of deforestation caused by the application of protection rules. Their results do not confirm the presence of such an effect in any location on nearby locations (Andam et al. 2008; Gaveau et al. 2009).

2.2 The impact of protected areas on deforestation

Policy makers often establish protected areas to preserve environmentally sensitive areas because deforestation has negative effects on the environment. In the Amazon, for example, to reduce deforestation, 487 000 km² of protected areas were created between 2003 and 2006. These areas now occupy 42% of the land area. Empirical studies that have examined

their impact on deforestation have shown that their ecological characteristics (level of rainfall, slope, and surface temperature) and status (belonging to indigenous populations) have an influence on deforestation (Deininger & Minten 2002; Mertens et al. 2002; and Mertens et al. 2004).

However, identifying the impact of protected areas on deforestation faces the problem of endogeneity bias related to the localization of protected areas. Indeed, deforestation and protected areas have in common the same explanatory factors (presence of roads, fertility, socioeconomic characteristics, agricultural expansion, etc.) and are not randomly distributed within the regions where they are assigned. To account for this problem, the authors usually build control groups using matching techniques in order to not overestimate or underestimate the impact of protected areas (Joppa & Pfaff 2009). The matching is based on the observable characteristics of protected areas or surfaces to identify control groups (without protected areas) with characteristics similar to those of the treated groups (with protected areas). The underlying idea is that deforestation would have evolved similarly in both groups if there were no protected areas. The difference between deforestation rates observed in these two groups can then be attributed to the presence of protected areas.

Cropper et al. (2001) studied the impact of the probability that an area is protected on the probability of being deforested. To do this, they consider these two decisions simultaneously using a bivariate Probit model to consider the localization bias. This method allows for identifying the localization bias using as control variables characteristics of the location of the surfaces (gradient, altitude, fertility, the distance to roads, etc.). According to their results, the probability that an area is protected does not have a significant effect on the probability that this area is deforested. In the same sense, Chomitz & Gray (1996) and Deininger & Minten (2002) study the probability that surfaces in protected areas are subject to deforestation. They proceed by comparing deforested surfaces predicted by the model to deforested areas outside protected areas. They show that protection has a more or less favorable impact on the reduction of land surfaces.

Another method to control for the localization bias of protected areas is to instrument this variable in the econometric regressions. This is the method used by Sims (2010). Her study focuses on the impact of protected areas on socio-economic characteristics of

populations in Thailand and Costa Rica. According to this author, the reduction of deforestation is not the only positive effect assigned to the creation of protected areas in the region. Improving certain socioeconomic characteristics within localities could partly be explained by the additional activities that develop around protected areas (infrastructure maintenance around the protected area, tourism, employment, etc.). However, the localization characteristics of protected areas (the distance to cities, the historical forest cover, etc.) that are conducive to the conservation of the ecosystem are not necessarily those that promote the development of economic activity. By instrumenting the surface of protected areas, Sims (2010) shows that protected areas improve the socioeconomic characteristics of certain localities.

Ferraro et al. (2011) identify conditions or physical characteristics that protected areas should meet to achieve both goals of reducing deforestation and improving socio-economic characteristics in a locality. Retaining the slope and distance to the nearest potential market as physical characteristics affecting the designation of land as protected in Thailand and Costa Rica, they show that the protected areas located between 40 and 80 km to the nearest potential market, and in which soil fertility is average, achieve both goals of reducing deforestation and improving socioeconomic characteristics. As for the cons, the areas with high agricultural potential, and where the designation of protected areas can significantly reduce deforestation, are problematic surfaces. Indeed, if people were initially poor, then the restrictions on access to protected areas encourage the stagnation of their level of poverty. The authors recommend taking these characteristics into account in the location of protected areas to reduce deforestation areas and improve the living conditions of households.

Taking into account the spatial aspect in the analysis of the impact of deforestation on protected areas remains marginal. The literature that considers this dimension focuses mainly on the spillover effects that protected areas can have on deforestation in forested areas that are in its vicinity. Gaveau et al. (2009), for example, test the hypothesis of a displacement of deforestation to neighboring surfaces by comparing the observed deforestation in protected areas with that observed in closest non-protected areas. They show that deforestation observed around protected areas within a 10 km radius in Sumatra and Indonesia is very low. They do not show displacement of deforestation. The results of

Andam et al. (2008) also point in the same direction. In this study, the authors compare deforestation in protected areas to that which takes place in a control group (located in a distant perimeter), using the method of matching. Their results show an absence of displacement effects of deforestation.

Several empirical studies have examined the impact of protected areas on deforestation. But they did not take into account the interdependence between deforestation and protected areas. Indeed, the need to protect forests, especially in the Amazon, usually appears with increased deforestation. As shown in previous studies, protected areas can curb deforestation and reduce its negative effects. These two decisions are interdependent and their determinants should be analyzed simultaneously. In addition, as with deforestation, taking into account spatial interactions in the establishment of protected areas should be explicit and effective, as ignoring them could bias econometric estimates.

3 Empirical Analysis

The main question addressed in this paper is whether the creation of protected areas in the Legal Amazon has reduced deforestation taking into account spatial interactions and the effects of leakage. To answer this question we use two empirical strategies. First, a spatial model with instrumental variables is used to control endogeneity bias related to the location of protected areas. Second, since the decisions of deforestation and creating protected areas may be interdependent, we use a spatial simultaneous equations model. The latter model also allows taking into account the effects of leakages related to the creation of protected areas.

3.1 Data and sources

The data used in this study come from several sources and were calculated as an arithmetic average over the period 2001-2011. We therefore have cross-sectional data over the period 2001-2011. Similar to Corrêa de Oliveira & Simões de Almeida (2010), we analyze the impact of explanatory variables on the average deforestation during the observation period. The description and sources of data used are summarized in Table 1.

3.2 Instrumental variables model

The first objective of this paper is to study the impact of protected areas on deforestation in the Legal Amazon area in Brazil. As discussed in the previous section, location of protected areas is endogenous (Cropper et al. 2001; Sims 2010). To correct this bias we use an instrumental variables model. To do this, we need variables that are correlated with protected areas but do not directly affect the level of deforestation in the municipality. In this study we assume that biological diversity (number of species of mammals and amphibians) is a good instrument. Indeed, one of the objectives of the creation of protected areas is the conservation of biodiversity (Palmer & Di Falco 2012; Dietz & Adger 2003). Thus, we should have more protected areas in municipalities with a high level of biodiversity. In addition, biodiversity should not have a direct impact on deforestation. But protected areas can compete with farming on the fertile land (Palmer & Di Falco 2012). We control this bias using variables of soil fertility, slope, length of roads (paved and non-paved), and the historical deforestation in 2000 (the first year of the study).

The administrative structure of Brazil (federal, state, and municipality) provides independent powers to municipalities. So, there could be strategic spatial interactions between municipalities. The Moran's I test and Robust Lagrange Multiplier test (see Table 2) confirm the presence of spatial interdependences (both spatial error and spatial lag models) between the decisions of deforestation in Legal Amazon municipalities. Therefore, the model to estimate is an instrumental model with both a spatial error and a spatial lag.

$$\begin{cases} Def = \alpha_1 WDef + \gamma_1 PA + X\delta_1 + \varepsilon \\ \varepsilon = \rho W\varepsilon + u \end{cases} \quad (1)$$

$$PA = X\delta_2 + Z\theta + \mu \quad (2)$$

where Def is vector of the average deforestation observed during the 2001-2011 period in the municipality, α_1 is a spatial autocorrelation parameter. W is a contiguity matrix. In this matrix, each element $w_{ij} = 1$ if two municipalities are neighboring and 0 otherwise. We normalize this matrix by dividing each element (i, j) by the sum of the line. $WDef$ is the vector of the spatially lagged endogenous variable which represents deforestation observed in neighboring municipalities, PA is a vector with observations on surface of protected areas,

and X is the matrix of control variables. ε assumed to be a vector of error terms of the model; it includes a spatially correlated part ($\rho W\varepsilon$) and an independently and identically distributed part (μ). Among the control variables, we have the forested area in 2000 (start date of the study), GDP per capita, percentage of agricultural GDP, density of the total population, slope of the municipality, length of paved and unpaved roads, rainfall, soil fertility, and dummy variables that capture the state fixed effects. Z represents the vector of instrumental variables excluded from the model.

Before estimating the system of equations (1) and (2) we check, empirically, the hypothesis of endogeneity of protected areas using the orthogonality test of Nakamura Nakamura (see Table 3). This test is to estimate the equation (2) by introducing the estimated error term ($\hat{u}$) of equation (1) obtained by OLS as an additional explanatory variable. This test validates the endogeneity hypothesis of the protected area because the parameter associated with ($\hat{u}$) is significantly different from zero.

To estimate this equation system, we used a Stata command of Drukker et al. (2011) for estimating spatial-autoregressive models with spatial-autoregressive disturbances and additional endogenous variables. But this command does not provide the estimates of equation (2). We, therefore, estimate the equation (2) by the method of OLS to ensure that our instruments explain the surface of protected areas in the municipality. The coefficients associated with our two instrumental variables are all significantly different from zero (see Table 4). We then perform a test of over-identification by regressing the error terms of the estimated model (equation 1) on the exogenous variables and instruments (see Table 5). The probability associated with the Wald test is equal to 1, thus, we can accept the null hypothesis of the coefficients associated with the explanatory variables in this model. These tests validate our instruments.

The results of a spatial lag model are not directly interpretable, due to spillover effects generated by the decisions of neighboring municipalities. To interpret the coefficients of this model, we must calculate the total marginal effects (direct effect plus indirect effect). To do this, we can rewrite equation (1) as follows:

$$Def - \alpha_1 WDef = \gamma_1 PA + X\delta_1 + \varepsilon$$

$$Def(I - \alpha_1 W) = \gamma_1 PA + X\delta_1 + \varepsilon$$

$$Def = (I - \alpha_1 W)^{-1} \gamma_1 PA + (I - \alpha_1 W)^{-1} X\delta_1 + (1 - \alpha_1 W)^{-1} \varepsilon$$

Following Kim et al. (2003),

$$(I - \alpha_1 W)^{-1} = \frac{1}{1 - \alpha_1}$$

The total marginal effect can be obtained by multiplying the estimated coefficients by the spatial multiplier $\frac{1}{1-\alpha_1}$**.** As argued by Kim et al. (2003), these results only hold for W row-standardized spatial weights matrices and for α_1 in the proper parameter space, i.e., $\alpha_1 < 1$.

The estimation results are presented in Table 6 and the marginal effects in Table 7. These results show that protected areas have a significant negative impact on deforestation. This impact is low. Indeed, an increase in protected areas of 1 km2 in a municipality reduces deforestation to 0.0055 km2. In addition, this study highlights the presence of spatial interactions between decisions regarding deforestation by municipalities and error terms of the model.

3.3 Simultaneous equations analysis

Instrumental variable regression only estimates the impact of protected areas on deforestation. However, interdependence between deforestation and protected areas exists, as the establishment of protected areas is dependent on extensive deforestation. What is more, the spatial autocorrelation test (Table 2) shows evidence of a relationship among surfaces of protected areas between municipalities that come from their spatial location. Spatial autocorrelation among units must then be taken into account in equation (2). Given the evidence of spatial autocorrelation, we can assume that the surface of protected areas and of deforestation in neighboring municipalities can affect decisions of deforestation and of the creation of protected areas in a given municipality. The estimated model becomes:

$$Def = \alpha_1 WDef + \beta_1 WPA + \gamma_1 PA + X\delta_1 + \mu \quad (3)$$

$$PA = \alpha_2 WPA + \beta_2 WDef + \gamma_2 WDef + X\delta_2 + Z\theta + \mu \quad (4)$$

In equation (3), Def is dependent variable, which represents deforested surfaces of land observed in municipality ; $WDef$ is the vector of lagged dependent variable that measures the effect of deforestation in neighboring municipalities, WPA is the vector of lagged explanatory variable that is exogenous and measures the effect of the creation of protected areas in neighboring municipalities, PA is the vector of surface of protected areas in municipality, and X is the vector of exogenous explanatory variables.

In equation (4), PA is the vector of dependent variable, which represents the surface of protected area in municipality, WPA is the vector of lagged dependent variable that measures the effect of creation of protected areas in neighboring, $WDef$ is the vector of lagged explanatory variable that is exogenous and measures the effect of deforestation in neighboring, Def is the vector of surface of land deforested in municipality that measures the effect of deforestation on the surface of protected areas, X is the same vector of exogenous explanatory variables of equation (3), and Z is the vector of exclusion variables that identity the model (numbers of mammals and amphibians).

To estimate this model, we used the method of Kelejian and Prucha (2004) for estimating simultaneous systems of spatially interrelated cross sectional equations. Table 8 presents the estimation results of simultaneous equations. The coefficient of the lagged variable in equation (3) is positive and significant. That provides evidence for complementary strategic interactions. This result is in line with the findings of the instrumental variable model. The more important the surface of protected areas in neighboring municipalities (WPA), the more important is the surface of land deforested in municipality i. However the more important the surface of protected areas in municipality i, the less important is the surface of land in municipality i. In other words, the importance of protected areas in neighboring municipalities acts as an incentive for deforestation. Indeed, an increase in protected areas of 1km^2 in a municipality reduces deforestation to 0.01030 km^2 (The marginal effects are presented in Table 7). Protected areas in the vicinity of a municipality have a positive influence on its deforestation. This means that the increase in protected areas in a municipality will result in an increase in deforestation in neighboring municipalities. This result lends support to the idea that, due to leakage effects, protected areas simply shift deforestation (Gaveau et al. 2009; Fearnside 2009; Soares-Filho et al. 2010). However, the total marginal effect of protected areas (effect of PA and WPA) is negative. This suggests

that, despite the existence of leakage effects, the creation of protected areas significantly reduces deforestation.

The results of equation (4) give evidence of substitutable strategic interactions. The coefficient of the dependent lagged variable (protected area) is negative and significant. The greater the creation of protected areas in neighboring municipalities, the less important is the surface of protected areas in a given municipality. Further deforestation has a negative and significant impact on the surface of protected areas in the municipality. From the marginal effects, we can say that an increase in deforestation of 1km^2 in a municipality reduces the surface of protected areas in this municipality to 43.5432 km^2 (the marginal effects are presented in Table 7). The results suggest, also, that the deforestation in neighboring municipalities ($WDef$) positively affects the surface of protected areas in a given municipality. However deforestation in a given municipality has a negative impact on the surface of protected areas. In others words, extensive deforestation in a neighboring municipality is an incentive for the establishment of protected areas in a given municipality while deforestation in the municipality is a disincentive.

3.4 Robustness check

As for robustness, the estimation of a simultaneous equations model has been done on two sub-periods (2001-2004) and (2005-2009). The choice for these two sub-periods is explained by the fact that the first sub-period is marked by a very high level of deforestation, while the second is marked by a considerable decrease of the phenomenon, due to an amplification of protective measures for forests. In fact, according to data from the National Institute for Space Research, between 2001 and 2004 the average annual rate of deforestation was greater than 20,000 km2, while between 2005 and 2011, it is still less than 6,000 km2. Over the same period, there has been an amplification of protective measures and the creation of protected areas. This can be visualized in Figure 1 of protected areas and deforestation presented above. The results of these two estimates of sub-periods are similar to those of the whole period, and can confirm not only the stability of the effects, but also the existence of interdependence between protected areas and deforestation in Brazil.

4 Concluding remarks

The creation of protected areas in the context of the Legal Amazon area addresses two major objectives: to help reduce deforestation and protect environmentally sensitive areas. During the last decade we have seen a significant reduction in the average annual rate of deforestation and a significant increase in surface area of protected areas in the Legal Amazon (2,000,000 km^2 today). That is why, in this study, we set the goal to analyse: (1) the impact of protected areas on deforestation; (2) the interdependence between surfaces of protected areas and deforestation, and (3) the existence of spatial interactions between deforestation and surfaces of protected areas created.

According to our results, the surface of protected areas and the level of deforestation adversely affect each other. We also show that there are complementary strategic spatial interactions (positive and a significant coefficient of spatial autocorrelation) in the decisions of deforestation and substitutable strategic interactions (a significant and negative coefficient of spatial autocorrelation) in the decisions to create protected areas.

In terms of public policy, these results suggest that the increase in protected areas in recent years in the Legal Amazon areas actually helped to reduce deforestation. This policy is thus effective and should be encouraged. In addition, the existence of spatial interactions in the equation of deforestation, as well as in the equation of protected areas, suggests a coordination of municipalities in the establishment of protected areas to make them more effective in terms of reducing deforestation and protecting and preserving ecosystems. Indeed, coordination may slow complementary interactions in deforestation decisions and could promote the establishment of ecological corridors that promote particular migratory species.

Despite the importance of these results, this study can be improved by exploiting the temporal dimension of our data using simultaneous equations panel models, taking into account the spatial aspect. This will allow us to take into account the temporal and individual effects.

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Appendix

Table 1. Variables, definitions, and descriptive statistics

Variables	Description	Sources
Def	deforested area (km2)	Prodes
PA	protected areas (km2)	UNEP-Prodes
Number_PA	number of protected areas	idem
Federal	dummy variable = 1 if federal protected area designated by the federal government	idem
State	dummy variable = 1 if state protected area designated by the State	idem
Forest	forest area in km2 at start date of the study (2000 or 2004 depending on estimation)	Prodes
GDP_per_Capita	GDP per capita	IBGE
Agricul_GDP	% of agricultural GDP	IBGE
Density	density of the total population	IBGE
Density_Rural	density of the rural population	IBGE
Slope	average slope of municipality i	I Sciences, Elevation & Depth Map
Paved_roads	paved roads (km)	Departamento Nacional de Infraestrutura de Transportes (DNIT)
Unpaved_roads	unpaved roads (km)	idem
Rainfall	rainfall of municipality i	CRU TS 3.2 Université East Anglia 2012
Fertility_2	% of fertile land classified in rank 2	FAO (1997)
Fertility_3	% of fertile land classified in rank 3	idem
Mammals	total number of mammals	UICN
Amphibians	total number of amphibians	UICN

Table 2. Spatial autocorrelation tests

	Deforestation		Protected areas	
Test	Test statistic	P-value	Test statistic	P-value
Morans' I test	2.479**	0.013	2.847***	0.004
Robust LM_{Lag}	23.848***	0.000	7.275***	0.007
Robust LM_{Error}	3.057*	0.080	9.087***	0.003

Table 3. Orthogonality test of Nakamura Nakamura

Deforestation	**Coef.**	**Std. Err.**	**P-value**
PA	-.002693***	.0005887	0.000
Resid_PA ($\hat{u}$)	.0450097*	.0252102	0.074
Number_PA	.452751	.9433001	0.631
Federal	-10.2266*	5.948994	0.086
State	7.110211	5.864599	0.225
Forest	.0039963***	.0005351	0.000
GDP_per_Capita	-1.861845***	.6902854	0.007
Agricul_GDP	.7628195***	.1399373	0.000
Density	-.0220418	.0431836	0.610
Slope	-.0005134	.0040176	0.898
Paved_roads	.1488197***	.047559	0.002
Unpaved_roads	.0434556	.0297843	0.145
Rainfall_01_09	.001716	.0127079	0.893
Fertility_2	24.72548	15.26731	0.105
Fertility_3	28.55322*	17.03303	0.094
Rondonia	1.743184	16.72844	0.917
Acre	-51.53479**	21.88285	0.019
Amazonias	-70.78485***	18.04895	0.000
Roraima	-14.47486	30.47281	0.635
Pará	17.11196	14.62398	0.242
Amapá	-13.37414	30.7352	0.663
Tocantins	-16.96714	12.07772	0.160
Mato Grosso	-12.80896	12.51424	0.306
_cons	-49.58187	40.5596	0.222

Table 4. OLS estimation of protected areas (equation 2)

PA	Coef.	Std. Err.	P-value
Number_PA	19.12115	56.14209	0.734
Federal	-334.5865	338.1631	0.323
State	226.8113	344.9658	0.511
Forest	.8305306***	.0138256	0.000
GDP_per_Capita	15.43226	33.28979	0.643
Agricul_GDP	6.090768	8.999596	0.499
Density	.6533068	2.089787	0.755
Slope	.290781	.2155422	0.178
Paved_roads	-1.682691	2.955839	0.569
Unpaved_roads	-.3966959	1.909814	0.836
Rainfall_01_09	-.780362	.4928342	0.114
Fertility_2	-1037.389	795.8079	0.193
Fertility_3	-1743.895**	824.2841	0.035
Rondonia	3422.519***	816.9755	0.000
Acre	1433.918	1223.421	0.242
Amazonias	-3513.126***	933.992	0.000
Roraima	1286.707	1152.655	0.265
Pará	675.8377	585.2837	0.249
Amapá	1457.59	1077.58	0.177
Tocantins	1408.419***	464.8389	0.003
Mato Grosso	518.1593	542.7852	0.340
Mammals	**69.83424*** **	**17.3326**	**0.000**
Amphibians	**-99.84539*** **	**20.52301**	**0.000**
_cons	-3999.476	2471.511	0.106

Table 5. Over-identification test

Error terms of equation (1)	**Coef.**	**Std. Err.**	**P-value**
Number_PA	-.1498476	.838229	0.858
Federal	-.6288167	4.96473	0.899
State	.0048021	5.111749	0.999
Forest	-.0000784	.0002107	0.710
GDP_per_Capita	.0445277	.4926936	0.928
Agricul_GDP	-.0230511	.1368087	0.866
Density	-.0017245	.0314405	0.956
Slope	-.0003073	.0031378	0.922
Paved_roads	.0042017	.0443491	0.925
Unpaved_roads	-.0020489	.0286409	0.943
Rainfall_01_09	.0009319	.0069517	0.893
Fertility_2	-1.109804	11.73294	0.925
Fertility_3	-.4788844	12.0874	0.968
Rondonia	-12.4827	11.75768	0.288
Acre	-8.858439	17.6488	0.616
Amazonias	-5.020676	13.54445	0.711
Roraima	3.690782	16.07516	0.818
Pará	-2.642356	8.246869	0.749
Amapá	-14.50282	15.40922	0.347
Tocantins	-6.536191	6.726069	0.331
Mato Grosso	-1.487643	7.706027	0.847
Mammals	-.2204412	.2461729	0.371
Amphibians	.4086206	.3053852	0.181
_cons	-8.193359	35.86386	0.819
lambda	.3732115	.1981999	0.060
rho	-.1214484	.2555532	0.635
sigma2	2287.849	152.9582	0.000
Wald chi2(23)	4.8257	-	1.000

Table 6. Estimation results of instrumental variables model

Deforestation	Coef.	Std. Err.	P-value
PA	-0.0040717**	0.0015064	0.007
Number_PA	0.6246317	0.8981904	0.487
Federal	-12.55995**	5.744213	0.029
State	6.889649	5.718099	0.228
Forest	0.0053399***	0.0012788	0.000
GDP_per_Capita	-0.9896033*	0.5484028	0.071
Agricul_GDP	0.7602452***	0.1414736	0.000
Density	0.0332056	0.0327784	0.311
Slope	0.000702	0.0036837	0.849
Paved_roads	0.1739771***	0.0473072	0.000
Unpaved_roads	0.0453117	0.0302461	0.134
Rainfall_01_09	0.0076153	0.0090567	0.4
Fertility_2	15.25102	13.17911	0.247
Fertility_3	21.37597	14.22859	0.133
Rondonia	2.088952	11.19014	0.852
Acre	-36.18523**	16.24966	0.026
Amazonias	-78.84084***	15.19282	0.000
Roraima	-8.079565	18.92332	0.669
Pará	10.15148	10.02642	0.311
Amapá	-11.41063	18.59311	0.539
Tocantins	-10.70559	9.327439	0.251
Mato Grosso	-6.716296	9.562614	0.482
_cons	-44.76779	28.09276	0.111
lambda	0.2460787***	0.0673936	0.000
Rho	0.2705836***	0.0756645	0.000

Table 7. Marginal effects of instrumental variables model and simultaneous equations (2001 - 2009)

	Instrumental variables model	Simultaneous equations	
	Deforestation	Deforestation	Protected areas
WDef			11.0538
WPA		0.0008	-0.0795
Def			-43.5432
PA	-0.0055	-0.0103	
Number_PA	0.8819	1.4302	88.5177
Federal	-14.1522	-14.3671	-794.6418
State	8.1566	8.7015	513.784
Forest	0.0068	0.0105	0.8516
GDP_per_Capita	-1.1845	-1.0228	-42.9961
Agricul_GDP	0.9029	0.7624	35.82
Density	0.0377	0.0313	1.58199
Slope	0.001	0.0026	0.2159
Paved_roads	0.2166	0.1369	4.0306
Unpaved_roads	0.0536	0.0486	2.6362
Rainfall_01_09	0.0075	-0.0010	-0.3497
Fertility_2	15.3915	5.1580	-153.5696
Fertility_3	16.5648	5.6468	-467.905

Table 8. Simultaneous equations results and robustness

	2001-2009				2001-2004				2005-2009			
	deforestation		area_ap_tot		deforestation		area_ap_tot		deforestation_05_09_1		area_ap_tot_2	
	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.	Coef.	Std. Err.
WDef	0.4678377***	0.0732292	12.0091**	6.123357	0.4821192***	0.0684592	8.101882*	4.640513	0.4464987***	0.0766142	15.82003*	8.387351
WPA	0.0007995*	0.0004318	-0.0864217**	0.0277334	0.0035734***	0.00094	0.0033184	0.0455487	0.0005954*	0.0003283	-0.0870711**	0.0279544
PA	-0.0102767***	0.0013106	.	.	-0.0151829***	0.0014605	.	.	-0.007446***	0.0010079	.	.
Def	.	.	-47.30633***	6.63272	.	.	-44.14569***	4.619433	.	.	-58.151***	9.239931
Number_PA	1.430243	0.9014506	96.1676*	58.03819	100.945***	17.22767	6258.313***	763.3353	1.794355**	0.6860413	138.1007**	59.35506
Federal	-14.3671**	5.694003	-863.3162**	369.7742	70.42069***	17.80299	4523.188***	833.8238	-8.911193**	4.320825	-734.9985**	367.3792
State	8.701473	5.665642	558.1861	365.7333	9.723788	8.137902	590.8413	408.4188	6.656205	4.323638	551.8641	368.0812
Forest	0.0105436***	0.0011223	0.9252288***	0.0186151	0.0115871***	0.0008959	0.7054119***	0.0171763	0.0076664***	0.0008724	0.9223908***	0.0186143
GDP_per_Capita	-1.022765*	0.5435942	-46.71197	35.54714	-2.09423**	0.7926821	-109.3846**	40.24907	-0.9584807**	0.4180658	-61.30014*	36.24866
Agricul_GDP	0.7623579***	0.1400429	38.91567***	10.26965	116.2441***	18.94465	5690.185***	1048.752	56.67477***	10.74191	3799.055***	1024.122
Density	0.0313036	0.0323882	1.71871	2.091652	0.0451128	0.0483717	1.980307	2.451986	0.0163323	0.023179	1.278573	1.967041
Slope	0.0025876	0.0036624	0.2345655	0.2344255	0.005109	0.0051905	0.3344138	0.2607886	0.0026986	0.0028109	0.3130086	0.2366905
Paved_roads	0.1369486**	0.0468234	4.379031	3.223408	0.2669916***	0.065249	12.3303***	3.476514	0.1115618**	0.0355437	4.769544	3.250964
Unpaved_roads	0.0485618	0.0298672	2.864106	1.930179	0.0083633**	0.0428687	-1.099477	2.164534	0.0240135	0.0228457	2.163012	1.933805
Rainfall_01_09	-0.0010137	0.0091918	-0.3799482	0.613929	0.0455009	0.0140501	2.696395***	0.7072874	-0.0080565	0.0066714	-0.6398749	0.5926785
Fertility_2	5.157979	13.05833	-166.8414	841.4507	12.79702**	18.45074	464.5327	936.4536	0.6624451	9.918701	-320.184	840.7927
Fertility_3	5.646768	14.11942	-508.3422	906.954	23.5117	19.74606	960.2818	1006.453	0.2719887	10.71958	-736.1878	903.777
Rondonia	7.702389	11.24901	1767.477*	998.0969	4.917449	16.81452	1144.619	1098.154	7.650112	8.547138	2023.504**	1006.785
Acre	-22.34697	16.71802	-563.0104	1446.962	-67.23374**	25.88112	-2823.09*	1620.63	-15.38125	12.36218	-295.5069	1444.101
Amazonas	-85.03469***	16.13095	-6173.915***	1216.349	-115.7141***	24.13608	-6127.086***	1374.112	-58.86848***	11.73451	-5728.897***	1170.034
Roraima	31.1813	20.59352	1735.191	1423.59	27.16859	30.8044	1176.788	1651.334	28.23529*	15.64494	2222.108	1428.849
Pará	21.98124	10.27876	1266.881*	701.6971	-14.08605	14.65754	-1107.871	777.5989	24.29247**	8.050943	1698.41**	741.8391
Amapá	9.833545	19.4856	816.7834	1351.508	-0.0359168	28.80473	240.6115	1548.898	14.79171	14.4741	1416.329	1331.751
Tocantins	0.2269093	9.607198	624.6576	631.0509	-15.4467	14.14464	-828.5906	723.3028	1.494169	7.144097	786.3594	620.6694
Mato Grosso	0.3022895	9.618538	305.7167	652.3845	-7.536581	14.0255	-672.5865	742.5165	-2.929128	7.401034	136.8865	663.5595
Mammals	.	.	37.45083*	20.21893	.	.	16.61508	19.8492	.	.	37.7094*	21.65659
Amphibians	.	.	-45.31078*	24.11789	.	.	-34.87404	24.29791	.	.	-49.86185**	25.28773
_cons	-22.45175	22.13209	-3883.874	2761.65	-149.5863***	31.25761	-12690.53***	3020.897	-5.595872	16.80464	-3296.191	2845.022