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Analysis

Relationship between openness to trade and deforestation: Empirical evidence from the Brazilian Amazon

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ABSTRACT

One of the objectives of this paper is to investigate how international trade has affected the dynamics of deforestation in the Brazilian Amazon at the level of the municipality. This analysis focuses on the expansion of crop and cattle activities, and other determinants of deforestation such as GDP per capita, conservation areas and property rights. We combine standard econometrics with spatial econometrics to capture the socioeconomic interactions among the agents in their interrelated economic system. The data used in this study correspond to a balanced panel of 732 municipalities from 2000 to 2010. The main findings suggest that as openness to trade in the Amazon increases, deforestation also increases. We also find that it is the production of soybeans and beef cattle that drives deforestation in the region. The property rights indicator also has a significant impact in deforestation. Moreover, as the GDP per capita goes up, deforestation increases. The conservation areas have a negative impact on deforestation.

1. Introduction

Since the 1980s, it has been internationally recognized that tropical forests, which are home to much of the world's biodiversity, are also very important to global climate regulation (Barbier, 2001). In recent years, economic development in these forests, which are mostly located in very poor regions along the equatorial line, has resulted in substantial destruction of the forest cover. Finding ways to slow down this process has become one of the top priorities of any environmental development agenda, and the factors contributing to the current rapid deforestation deserve further investigation.

The Brazilian Amazon, the focus of this paper, is a large area (61% of the country) divided into nine states.[2] It is home to 12% of the population of Brazil. The overexploitation of the forest resources is driven, for the most part, by economic interests from outside the area. In the 1970s, the government provided subsidies and incentives for mining, crop, and beef production, and supported gigantic road projects that brought new settlers from other parts of the country into the rainforest frontier (Mahar, 1989). Federal and state governments failed to regulate this settlement, with the result that there is considerable confusion about the ownership of key environmental resources. For the last few decades, frontier regions of the Amazon have been a major scene of land conflicts between cattle ranchers, squatters, miners, indigenous groups, and public authorities. In addition, since the enactment of free trade agreements in the 1990s, international markets for timber and agricultural commodities have been driving further deforestation in the region (Brandão et al., 2006).

The connections between deforestation and cattle ranching, agriculture, poorly defined property rights, road construction, and population growth have been extensively studied (Reis and Guzman, 1992; Pfaff, 1999; Walker et al., 2000; Weinhold and Reis, 2001; Andersen et al., 2002; Mertens et al., 2002; Margulis, 2004; Chomitz and Thomas, 2003; Pfaff et al., 2007; Diniz et al., 2009; Araujo et al., 2009; Rivero et al., 2009; Barona et al., 2010). However, to the best of our knowledge, there are very few studies that investigate the relationship between deforestation and openness to trade in developing countries.

One objective of this paper is the examination of how economic variables, including international trade and the expansion of agriculture and the cattle industry, and political issues have affected the dynamics of deforestation in the Brazilian Amazon. We combine standard econometrics with spatial econometrics in order to capture the socioeconomic interactions among the local, regional, and international agents in the Amazon region.

This paper has five sections in addition to this introduction. The second section presents a review of the literature and compares the theoretical models adopted in this work with models applied in other studies. The third section presents the main hypothesis. The fourth section discusses the methodology, data, and specifications of the estimating models used to test the relationship among explanatory

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[2] These states are Acre, Amapá, Amazonas, Mato Grosso, Rondônia, Roraima, Tocantins, Pará and parts of Maranhão (Fig. 1).

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variables and deforestation. The fifth section presents the results. The main results indicate a positive relationship between the economic variables examined, as well as the property rights indicator, and deforestation. The sixth section presents our conclusions.

2. Literature Review and Theoretical Background

Angelsen and Kaimowitz (1999) discuss more than 140 published studies that assess the causes of deforestation, classified according to two criteria—scale and methodology. The scale criterion concerns the unit of analysis—microeconomic (households, firms or farmers), regional, or macroeconomic (national). The methodology criterion classifies studies as to whether they are analytical, empirical, or simulation models. Angelsen and Kaimowitz rank the variables used by models of deforestation as: (1) the magnitude and location of deforestation; (2) the agents of deforestation; (3) the variables selected; (4) the parameters affecting agents' decisions; and (5) macroeconomic variables and policy instruments.[3]

Both classifications, in terms of criteria and type of variables, may be important for assessing the strengths and weaknesses of the works in different contexts of analysis. Microeconomic models use microdata and tend to focus on the specific behavior of landowners (or families) (e.g., Bluffstone, 1995; Angelsen, 1999; Chomitz and Thomas, 2003) in relation to deforestation. These models consider the existence of credit and subsidies for agricultural production, years of schooling of the landowners, and land use intensity. However, they ignore of broader causes of deforestation, such as the indirect effects of foreign trade and paved roads in the area of forest cover.

The empirical macroeconomic models use aggregate data, which can be found relatively easily, even for developing countries such as Brazil, Ecuador, Indonesia, Malaysia, and Thailand (Allen and Barnes, 1985; Cropper and Griffiths, 1994; Deacon, 1994; López and Galinato, 2005). One of the main data sources is the Food and Agricultural Organization (FAO), which provides information such as soil type, forest coverage, and population density. However, aggregated data aggregated are represented as average figures, often for a number of regions, which might distort the accuracy of the estimates for any given area. In Brazil, the adoption of a state-level analysis of deforestation from aggregate data is undesirable, since the dynamics of deforestation are quite different in different states.

Regional models are an appropriate solution in these cases, because they are based on local data and can be used to analyze an issue, such as deforestation, in a broader context than at the micro level. In addition, the regional-level model, with its disaggregation of data, allows a higher-quality analysis about the region under study than the macro-level analysis. In other words, the use of regional data allows researchers to avoid making erroneous inferences from highly aggregated data while ensuring that local features are incorporated into the analysis.

The major empirical findings with regard to the drivers of deforestation in developing countries emerge from Allen and Barnes (1985) and Angelsen and Kaimowitz (1999). They found substantial evidence that deforestation is likely when forested lands are more accessible; when prices of agricultural commodities and timber are high; when rural wages are low; and when there are opportunities for trade. On other hand, they did not find evidence that increases in population, migration, productivity, land tenure, input prices, land markets, and poverty per se contribute directly to deforestation.

Cattle ranching, and more recently, the capital-intensive production of soybeans for supplying foreign markets, particularly China, have put great pressure on the Brazilian rainforest. Nowadays, Brazil is one of the largest exporters of soybeans and the world's largest exporter of beef: one third of all beef exports are from the Amazon (McAlpine et al., 2009). Margulis (2004), analyzing land use data, found that cattle ranching has been one of the major drivers of deforestation. However, he suggests that large and mid-size farms have contributed more to deforestation than smaller farms.

In the Brazilian Amazon, one important issue is the weak enforcement of property rights, particularly in public lands. If public land is not incorporated and legally protected, it is open to illegal occupation (Fearnside, 2001). Fearnside reports that violent conflicts for land between ranchers, small farmers, squatters, and indigenous tribes are common in the region, particularly in the so-called "arc of deforestation," a large tract of land on the southern and eastern fringes of the Amazon Basin. The majority of "private" lands are concentrated in medium and large properties (>100 ha) or vastly larger ones (>2000 ha) (McAlpine et al., 2009). In fact, farmers have an incentive to clear large parts of virgin forest; otherwise, they would lose their land to expropriation or to invasion (Fearnside, 2001).

There are no official statistics about the enforcement of property rights in the Amazon states. Araujo et al. (2009) used proxies for the lack of enforcement, such as the number of land conflict-related homicides and expropriation initiatives undertaken by the INCRA, the government agency responsible for the supervision and distribution of land in public lands. They showed that most landholders do not have legal title to their land, and insecure land property rights contribute to higher rates of deforestation.

One report published by the researchers of NGO Imazon in 2010 estimated that the state of Para is one of the most affected by land uncertainty in the Amazon region (Brito and Barreto, 2010). They report that 36% of Pará territory lacks well-defined land rights, and it is in the undefined portions of the territory that 70% of the deforestation occurs.

A handful of studies have looked directly at the relationship between the degradation of renewable natural resources and international trade (Chichilnisky, 1994; Brander and Taylor, 1996; and Ferreira, 2004). Generally speaking, the conclusion of these studies is that if property rights to the environmental resource in question are ill-defined, then trade between two countries does not make both better off in terms of resource allocations and income, as is usually claimed by the proponents of international trade. Chichilnisky, for example, assumes a trade agreement between two hypothetical countries—a "north country" and a "south country"—where the property rights to a natural resource in the south country, which exports goods based on that natural resource, are ill-defined. She shows that although trade is able to equalize output and factor prices between north and south, it does not improve resource allocation in the south country. Since the south is poor and owns a subsistence sector (labor), tax policies on the use of the resource that decrease the price of the resource would lead to even more extraction (overproduction) of the common property.

Ferreira (2004) supports the idea that the lack of property rights in an exporting country leads to overexploitation of commonly owned resources. She built a model that exploits the difference between the marginal and the average product of labor in two hypothetical countries, also called "north" and "south," assuming that both countries share similar technological levels, stocks of natural resources, and available labor. The main reason for trade is not the difference in the resource abundance in the two countries, but the difference in property rights over natural resources: the north has better-defined property rights than the south. Thus, increases in prices brought by trade shift up the value of the marginal product and the value of the average product curves, inducing labor migration from the manufacturing sector to the harvest sector in the south. Ferreira concludes that even as the south becomes a net exporter, it experiences losses from trade. In addition, the elimination of trade distortions enlarges the effects of property rights distortions, which also damage the south country.

Brander and Taylor (1995) analyze another hypothetical open, small-country economy. Natural resources are abundant, and property rights are not enforced. In accord with Ricardian economics, the authors

[3] See Kaimowitz and Angelsen (1998) for the full report.

show that under free trade, the small country, even with a comparative advantage in natural resources, may still suffer losses in economic terms and the use of natural resources.

Some of these theoretical conclusions have been confirmed empirically, but there are still few studies that try to explain the linkages between deforestation and international trade. Most focus on traditional supply models or partial equilibrium trade models for specific agricultural or forest commodities[4] or focus on cross-country analyses. Here, we summarize the ones that are more directly related to our research questions. For instance, Ferreira (2004) analyzed data from 92 countries for 1961–1994 and found that the usual openness indicator (X + M) / GDP) is a significant predictor of deforestation, but only when factors such as institutional expropriation and bureaucratic corruption are operating. Using household surveys for Brazil, Indonesia, Malaysia, and the Philippines, López and Galinato (2005) found that openness to trade between 1980 and 1999 increased forest cover in Brazil and the Philippines, but decreased forest cover in Indonesia and Malaysia. The *net* impact of trade openness on forest cover for the four countries was small.

Using data of 1989 for Ghana, López (1997) found that the reduction of tariff protection and export taxes resulted in losses of biomass (natural fertilizer used by farmers) of 2.5%–4%, and that the overexploitation of biomass had little impact on national income. More recently, Arcand et al. (2008) have shown theoretically that depreciation of the real exchange rate and weak government regulation result in more deforestation in developing countries. In an empirical application based on annual data for 101 countries between 1961 and 1988, they did not reject any of the hypotheses above.

Barbier (2000) developed a basic model to demonstrate how input and output price changes influence the conversion of forestland to agricultural production. His major hypothesis is that any political reforms toward economic liberalization will impact domestic prices, impacting the incentives for agricultural land expansion. Agricultural sectors in the developing world, such as in the Amazon, are commonly characterized by low input and extensive land use, which is a key issue. If returns for this sector increase, the result is usually more demand for land and more pressure on natural resources. However, looking at structural adjustments, trade liberalization, and agricultural development in Ghana and Mexico, Barbier found the opposite. Trade reforms can actually mitigate the impact on forestland when farmers increase their investments and efforts to improve the efficiency of their input use and raise their productivity.

3. Main Hypothesis

The Amazon region has specific characteristics that distinguish it from other regions of Brazil. One is the lack of clarity about property rights and the enforcement of these rights. Land occupation is motivated by profit (Angelsen, 1999), and without regulation, logging and ranching activities lead inexorably to deforestation. Sustainable land use also aims to make profit, but with less impact on the land. Differences in terms of land use practices may determine the level of deforestation (Hargrave and Kis-Katos, 2013). The degree of deforestation is associated with four principal factors: economics, property rights, legal restrictions, and natural conditions.

The cost of deforestation in the Amazon region regarding economic conditions is directly related to the expansion of the agricultural frontier. Notably, the production of soybeans and the expansion of cattle ranching have contributed substantially to the conversion of forest areas into productive areas. Therefore, it is expected that the increase in production of these activities will cause an increase in deforestation. Likewise, it is expected that intensified logging will positively affect deforestation. Measuring local development by GDP per capita can generate ambiguous results; Brown and Pearce (1994) found that an increased GDP usually implies increased participation of the industrial and service sectors, rather than in the agricultural sector.[5] A higher GDP means that more resources are available to increase the productivity of the agricultural sector without increasing deforestation (Panayotou and Sungsuwan, 1989)—yet the increase in the level of local income results in increased demands for food and lumber.

One of the drivers of the expansion of the agricultural frontier in the Amazon region is the expectation of returns from international trade. In this region, the proportion of the GDP due to exports grew from 11% in 2000 to 31% in 2010, while for Brazil as a whole, it remained about 10% in the same period (from 8.5% to 10.7%).[6] These figures indicate that openness to international trade might play an important role in deforestation of the Amazon region. It is a fact that in the 2000s, Brazil has become one of the largest exporters of agricultural commodities in the world, particularly soybeans to supply markets in China and the U.S. That being said, the effects of openness to trade on deforestation can also be ambiguous. If openness to trade results in an increase in *exports*, it places pressure on the tropical forests; however, if openness results in increased *imports*, the incentives to cut down the forest are reduced.

As mentioned before, the poor definition of property rights in the Amazon region generates a range of uncertainties (Araujo et al., 2010). For this study, we use a variable called *property rights* as an indicator of the proportion of the total agricultural settlements in the Amazon rain forest that is controlled by squatters. It is expected that this indicator will correlate positively with deforestation. We assume that the vast majority of small and large farmers' settlements have grown up outside the official colonization areas, on public lands or unused private lands or along the major paved roads in the Amazon region as reported by Araujo et al. (2009). In addition, since President Lula's government took office in 2002, there has been also strong evidence that where big infrastructure projects such as hydroelectric power plants (e.g., Belo Monte, Santo Antonio and Jirau Dams) are being built, there are also bloody conflicts in the regions surrounding these construction sites. According to INCRA, the official institute responsible to monitor the land conflicts in the country, only in the southeast of Para state, there are between 14,000 and 15,000 families in tents without any infrastructure living the surroundings of dams .[7] In summary, most of them do not have legal titles, and enforcing property rights might be very costly (Araujo et al., 2009).

The declaration of environmentally protected areas is intended to serve as a legal barrier to deforestation. Protected areas in Brazil include (1) strictly protected areas, (2) areas of sustainable use, and (3) indigenous areas. These are all protected by both federal and state laws. Strictly protected areas include parks and ecological stations, and provide complete protection to the local environment. Sustainable-use areas include extractive reserves, where exploitation is permitted under criteria of sustainability. Indigenous areas are areas populated exclusively by Indians. Protection of these areas may work as a strong defense against deforestation (Soares-Filho et al., 2010; Amin et al., 2014.). However, there is evidence that the protection of indigenous lands may have little practical effect, if it is applied to areas where the pressure for deforestation is low (Joppa and Pfaff, 2010).

In one specific case, two geo-climatic factors are used to explain deforestation: temperature and rainfall.[8] Some agricultural crops fail when temperatures increase, while others may be stimulated under the same conditions. Similarly, increased rainfall can reduce agricultural productivity of some crops, while increasing that of others. Farmers may

[4] See Kaimowitz and Angelsen (1998) Section 5.3 Trade and Commodity models.

[5] In another context, it seems unlikely to be the case for the Amazon region, is that the increase in GDP per capita can also generate increased demand for environmental quality.

[6] www.ipeadata.gov.br.

[7] O Estado de São Paulo (2015) (Access at: http://infograficos.estadao.com.br/public/especiais/favela-amazonia/capitulo-7.php.

[8] Other characteristics such as soil type, topography and distance between municipalities can affect deforestation. However, as well as other characteristics that do not vary over time, such factors are treated in the models.

Table 1
Variable definitions and summary statistics.[1]

Variable	Description	Mean	SD	Min.	Max.
Deforestation	Deforested area (km^2)	955.43	1192.27	0.000	16989.90
Openness (1)	(X + M) / GDP where X and M are, respectively, the import and export values of all products, and GDP is the gross domestic product	0.064	0.306	0.000	11.504
Openness (2)	(X + M) / GDP where X and M are, respectively, the import and export values of primary products, and GDP is the gross domestic product	0.043	0.208	0.000	9.181
GDP pc.	GDP per capita	3927.0	4961.8	716.4	84494.6
Soybeans	Soybean production (tons)	20153.5	106308.3	0.0	1840800.0
Cattle	Number of heads	85055.0	128507.6	0.0	2022366.0
Wood	Timber and firewood production (tons)	33940.7	89236.0	0.0	1530000.0
Non-wood[2]	Non-wood products (tons)	343.7	1375.7	0.0	35381.0
Settlement	Number of settlements	40.1	251.2	0.0	7360.0
Landowner	Land tenure status: landowner (number of agricultural establishments)	638.8	807.0	0.0	9278.3
Tenant	Land tenure status: tenant (number of agricultural establishments)	37.4	166.1	0.0	5966.9
Squatter	Land tenure status: squatter (number of agricultural establishments)	95.0	215.7	0.0	4538.7
Property rights indicator	Proportion of squatter settlement in the total of establishments	0.0810	0.1501	0.0	0.9448
Federal protected areas	Federal protected areas (km^2)	806.4	3818.2	0.0	56796.3
State protected areas	State protected areas (km^2)	685.7	3218.4	0.0	60563.4
Indigenous areas	Indigenous areas (km^2)	1224.6	4923.8	0.0	67223.0
Temperature	Annual averages of quarterly estimates averages of temperature (degrees centigrade)	26.285	0.996	22.369	28.262
Rainfall	Annual averages (based on quarterly estimates) of rainfall (millimeters)	164.512	34.435	91.634	279.994

[1] N = 8602 observations for 782 municipalities.
[2] Fruits, oils, medicinal plants, latex, etc.

respond to reduced productivity of a given crop either by abandoning it, reducing pressure on the rainforest, or by planting an increased area in order to achieve the level of initial production, thus increasing pressure on the forest.

4. Methodology

4.1. Data

This study used information from a balanced panel of 782 municipalities for the years 2000 to 2010, totaling 8602 observations. These municipalities are part of a PRODES (Program for the Estimation of Deforestation in the Brazilian Amazon) project funded by the Brazilian government to monitor the level of deforestation in the Brazilian Amazon. These municipalities form the so-called Legal Amazon. Table 1 shows the description of each variable used, as well as its mean and standard deviation.[9] All variables were standardized to perform the regressions.

Deforestation data were provided by The National Institute of Spatial Research (INPE), which collects and annually publishes rates of deforestation for all 782 municipalities that constitute the Legal Amazon, based on geo-referenced satellite images (INPE, 2014).[10]

The *openness to trade* indicator is the total volume of foreign trade, corresponding to the sum of exports and imports, as a proportion of GDP. The export and import data were obtained from the Ministry of Development, Industry, and Foreign Trade (MDIC), and the GDP data from the Brazilian Institute of Geography and Statistics (IBGE). Openness to trade (X + M) / GDP is subject to geographic factors: for instance, logging is possible only in regions where there are forests; soybean farming is possible only in regions that offer suitable climate and soil conditions. Performance in terms of export or import is also related to local factors (e.g., transportation, credit availability). Companies set up to export Brazilian products are more efficient if they are located in regions that provide better production conditions.

The data relating to the yields of *soybeans* were obtained from the IBGE database called SIDRA, which provides information about agricultural production in the municipalities. Data on *firewood*, *timber*, and *non-wood* extractives were obtained from this same database. The variable *non-wood* variable refers to aromatics, medicinals, dyes, rubber, waxes, fibers, non-elastic gums, charcoal, and tanning oil derived from vegetable products. The data on head of *cattle* were extracted from the SIDRA database (IBGE, 2014). GDP per capita was included in order to control the effect of the economic scale of the municipalities. This independent variable was added at the expense of a density variable, as these variables are highly correlated.

The export of *soybeans* and *cattle* has increased dramatically in recent years, so these variables are important factors in the investigation of how openness to trade affects deforestation. There are three reasons for the rise in exports: (1) international increases in the price of agricultural commodities caused, in part, by the economic expansion of China; (2) the devaluation of the national currency (the Brazilian real) against the U.S. dollar since 1999; and (3) the availability of land to increase crop yields, i.e., the opportunity cost of deforested land. These conditions have stimulated the agricultural sector to produce more commodities, mainly for export and also domestic markets.

The combination of these elements makes Brazil's agriculture highly competitive, facilitating foreign sales. Therefore, the focus of this work is to investigate how the possibility of conversion of forest to other uses may be associated with foreign trade.

The inclusion of other controls aims to add further exogenous explanations for the deforestation of Brazil. The *settlement* variable concerns the number of settlements; one settlement can accommodate more than one family.[11] This variable reflects population changes due to agrarian reform projects. The variables *landowner*, *tenant*, and *squatter* are included to examine how property rights may affect deforestation. Each variable relates to a different status of land ownership. The indicator of *property rights* refers to the proportion of establishment controlled by squatters. Data were obtained from the Agricultural Census of 1996 and 2006. Since the information is available only for census years, we assume a geometric evolution trend in the variables for the period between 1996 and 2006 and for the period after 2006 up to 2010.

[9] Some variables had missing observations for some municipalities in a few years of the study's period. In order to overcome this problem, geographically weighted estimates were made for generating those observations. The procedure involves estimation by the OLS procedure with the following specification: $m = \alpha + \beta_1 x + \beta_2 y + \beta_3 x^2 + \beta_4 y^2 + \beta_5 x^3 + \beta_6 y^3 + \varepsilon$, where x and y represent latitude and longitude of the centroid of each spatial unit; m refers to the vector of variables used in the econometric model to determine the dynamics of the deforestation that had missing observations; β^i is the vector of coefficients to be estimated for each i, where i indicates the relevant variable with missing observations and; ε the error term.

[10] Further information about the methodology of estimating the rates of deforestation can be found at http://www.obt.inpe.br/prodes and Câmara et al. (2006).

[11] www.ipeadata.gov.br.

The variables of *federal and state protected areas* and *indigenous areas* aim to control for conservation areas. Each variable corresponds to an administrative court. The data on federal and state protected areas were provided by the Department of Protected Areas (Secretaria de Biodiversidade e Florestas do Ministério de Meio Ambiente/MMA), and the data on indigenous land by the Socio-Environmental Institute/ISA.[12] The information on temperature (°C) and rainfall (mm) are from the Climatic Research Unit (CRU/University of East Anglia) database and correspond to the mean values for the thirty years between 1961 and 1990. In order to obtain the information annualized for the period 2000–2010, we used climate change projections for the next 30 years generated by the regionalized model PRECIS from CPTEC/INPE.[13] Climate variables were used as instruments of some economic variables on selected models.

Fig. 2 provides some background on the relationship between foreign trade, yield, and production area in Brazil. Graphic (a) shows the yields of soybeans in Brazil, as well as the area (ha) in production. Note that increases in production are directly related to increases in the area used. The land devoted to livestock has also increased over the years (graphic (b)). Graphic (c) shows that both the export volume of soybeans and the total export volume of goods from Brazil have increased significantly since the early 1990s. Finally, graphic (d) shows that the volume of imports into Brazil has decreased from 30% in the 1980s to an average of less than 10% in the 2000s.

These graphs show that there has been an increase in both land use and agricultural production in Brazil in recent decades, as well as an increase in exports and lower barriers to trade on the entry of foreign products. There appears to be a positive relationship between the expansion of agricultural activity, growth of land use, and growth of foreign trade. Thus, this study sought to determine whether the increase in land use for agricultural purposes, which in Brazil is often associated with the conversion of forest to crop or livestock, is actually associated with the intensification of foreign trade.

4.2. Empirical Implementation

The objective of this study is to investigate how openness to trade affects deforestation affects deforestation. This relationship can be described by the following model:

$$Y_i = f(X_i, \beta) \tag{1}$$

where Y_i is the dependent variable, deforestation; X_i is a vector of explanatory variables, including openness to trade; and β is the parameter vector.

Eq. 1 schematizes the relationship that we want verify. This could be estimated using OLS; however, since we have data available over time for each unit cross-section, the data are in panel format. It is well known that one of the main advantages of using panel data is to control for observed and also for unobserved characteristics (Baltagi, 1995). In such cases, fixed effects and random effects specifications are the most commonly used models in applied work.

First, consider the standard panel data model:

$$Y_{it} = X_{it}\beta + v_{it}, \mathrm{i} = 1, \ldots, N, \mathrm{t} = 1, \ldots, T \tag{2}$$

and

$$v_{it} = \mu_i + u_{it} \tag{3}$$

where Y_{it} is the dependent variable, X_{it} is a vector of explanatory variables; μ_i is the time-invariant individual component, and u_{it} is the error term. The vector β is the parameter(s) to be estimated.

The consistent estimation of Eq. (2) by a pooled OLS approach requires that the explanatory variables—both the error term and the unobserved effect—are uncorrelated. The fixed effects model assumes that the intercept changes between the units of cross-section, but does not change over time. The fixed effects specification allows that different intercepts may be used to capture all the differences between the units of cross-sections. The random effects model assumes that the behavior of both the units of cross-section and the time is unknown. Therefore, the behavior of these units of cross-section and the time can be represented in the form of a random variable, and the resulting heterogeneity is treated as part of the error term. Moreover, the random effects model assumes that the unobserved term is uncorrelated with the explanatory variables (Johnston and Dinardo, 1997).

4.2.1. Endogeneity Issues

The fixed effects estimation has the advantage of controlling for unobserved characteristics of the municipalities that may affect the dynamics of deforestation in the Amazon. However, one can expect that adding economic variables generates endogenous effects in terms of response to deforestation. As a result, the estimated coefficients could be biased. The main concern regarding bias lies in the variables of *openness to trade* and *GDP per capita*.

It is expected that deforestation increases the level of economic activity. The increased level of economic activity encourages yet more deforestation, ceteris paribus, with the potential for greater profits. Thus, deforestation encourages more deforestation via economic mechanisms. Similarly, the level of openness to trade has an endogenous relationship with deforestation through incentives that increase the expected return with foreign trade. In both cases, the effects of these economic activities could be underestimated, generating more discrete estimates.

In order to address these issues, three strategies were adopted. The first concerns the instrumental variable estimation. Because changes in temperature and precipitation can lead to different economic effects depending on the physical characteristics of regions and their initial economic profiles, the variables *temperature* and *precipitation* were used as instruments in all estimations. Temperature and rainfall are strongly associated with the economic activities of the municipalities of the Amazon region, which rely heavily on the production of primary goods.[14] Because of the association between economics and property rights, the land tenure status variables were also used as instruments jointly with climate variables.

To address the possibility of endogeneity of explanatory variables, the model was re-estimated using the Arellano–Bover/Blundell–Bond GMM estimator (Arellano and Bond, 1991; Arellano and Bover, 1995). The method of Arellano–Bover/Blundell–Bond is basically to use GMM to estimate the model in difference, using lags as instruments for the differences of all the endogenous explanatory variables.[15] The purpose of this estimation is to provide alternative insights in terms of instruments for the potentially endogenous variables and in methodological terms, since other estimates are considered fixed effects.

The second strategy considers the estimation of two alternative models for the variable *openness to trade*. The first variable of openness to trade, *Openness 1*, considers exports and imports of all possible goods. *Openness 2* considers the trade of primary goods only. These two types of openness can lead to different effects on deforestation. Since a high

[12] Protected areas include ecological stations, forests, natural monuments, parks, wildlife refuges, biological reserves, extractive reserves, private natural heritage reserves, sustainable development reserves, and fauna reserves. There is no overlap between these protected areas and indigenous lands.

[13] These projections consider different assumptions about the global socioeconomic trajectories to establish the effects on climate dynamics. In the present work, the projections used consider the A2 climate change scenario from IPCC (2007).

[14] Climate change may affect deforestation via economic activities, since variations in temperature and rainfall may lead certain activities become more profitable than others (Féres et al., 2008). For example, cattle can become more productive and coffee less productive in a certain region. The change in net profitability of certain activity can encourage or discourage deforestation (Chomitz and Thomas, 2003; Kirby et al. 2006; Arima et al., 2007; Aguiar et al. 2007).

[15] System GMM.

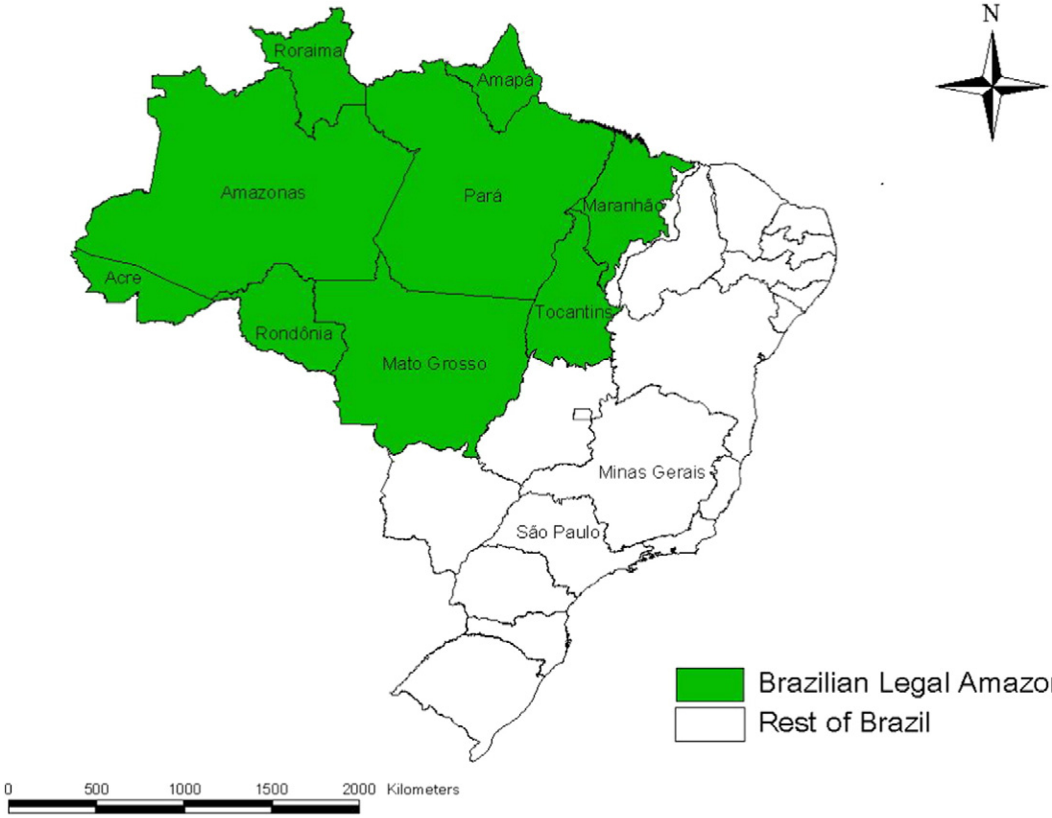

Fig. 1. Brazilian Legal Amazon.

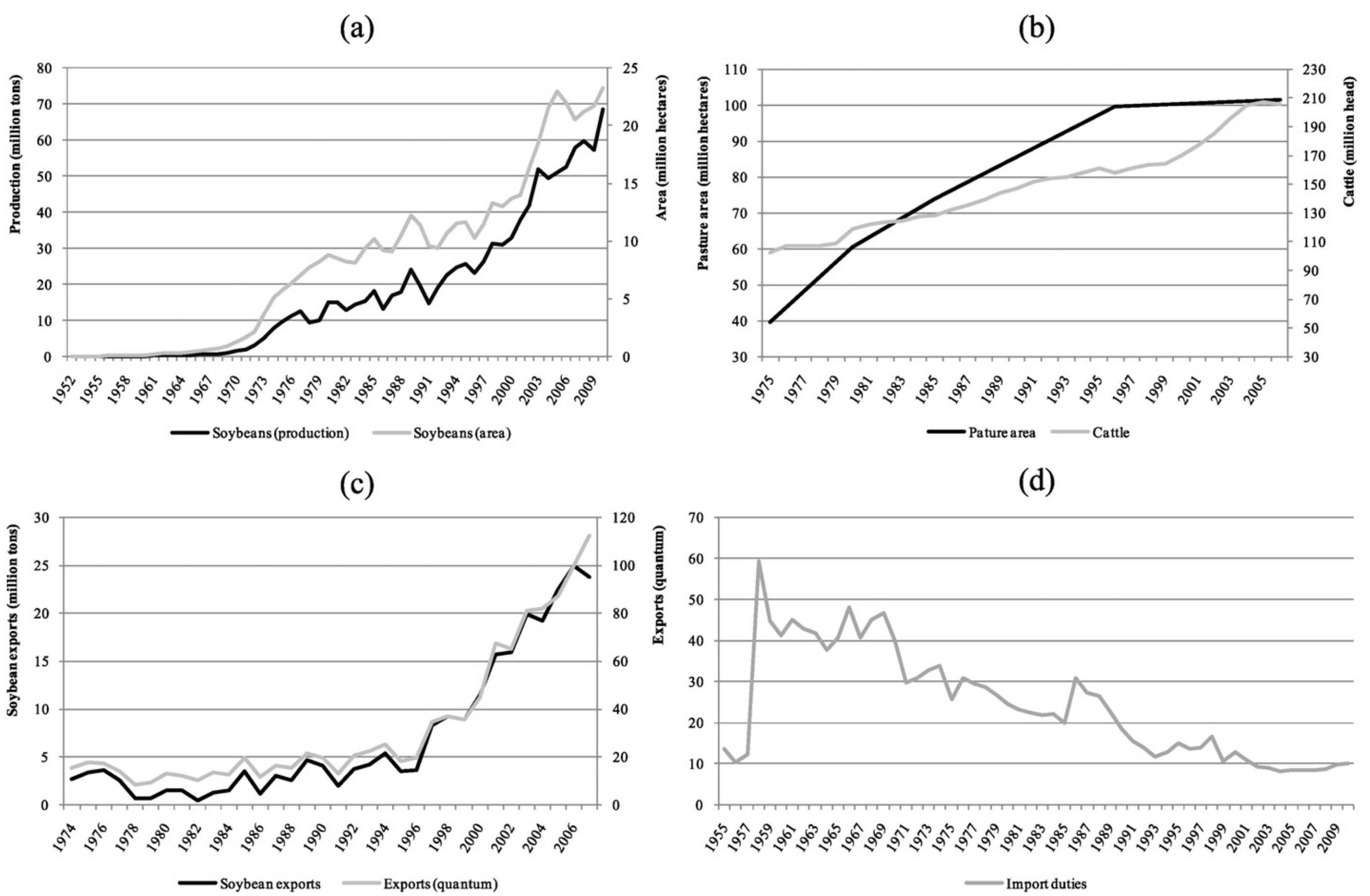

Fig. 2. Agricultural production and foreign trade of Brazil.

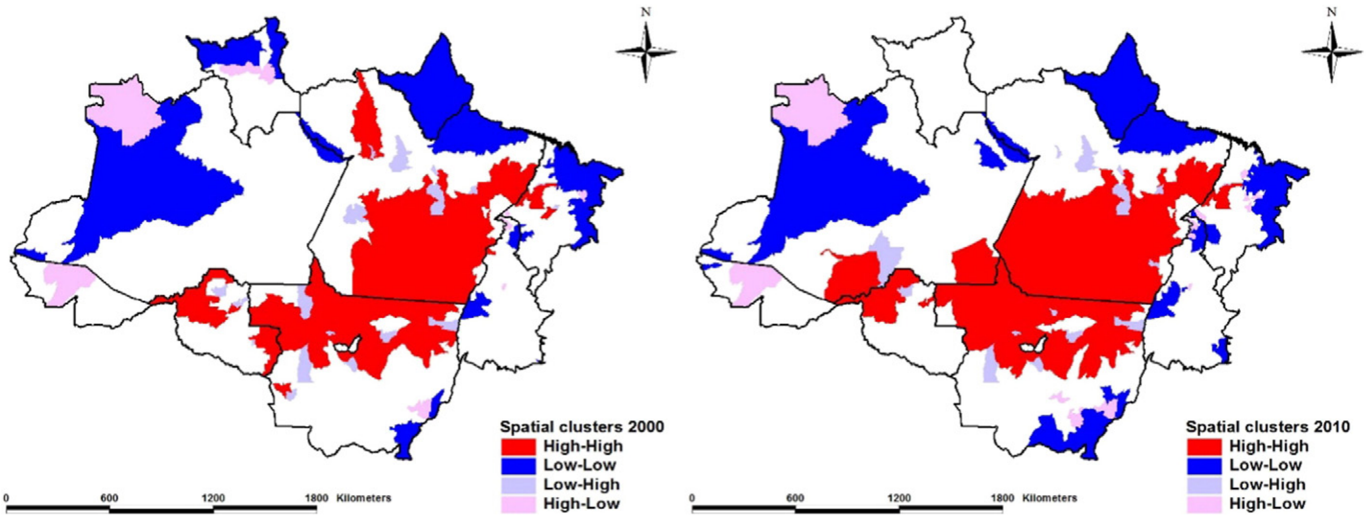

Fig. 3. Cluster map of *LISA* statistics of deforestation in 2000 (left) and 2010 (right).

proportion of the goods produced in the municipalities of Legal Amazonia are primary goods, most of the tradables are expected to be primary goods.

The third alternative includes only the municipalities that perform some international trade in the estimation. In general, we expected different effects on deforestation from these communities than from ones that do not engage in international trade.[16] However, international trade in a given municipality might increase or decrease deforestation in neighboring municipalities. Furthermore, the deforestation of the surrounding municipalities may be important in explaining the deforestation of the trading municipality. Such possibilities are raised below.

4.2.2. Spatial Issues

In the presence of spatial autocorrelation, the adoption of the procedures described above is not enough, and some extensions specific to panel data have been developed (Elhorst, 2003). It is worth mentioning that these extended models (Eqs. (4) and (5)) take into consideration the same properties as the traditional panel data ones; the major difference consists in adding more explanatory variables, to take into account the spatial effect. Nevertheless, no special treatment is given to residual values of these regressions.

Now, consider the following models that take into account the spatial effect (Anselin and Bera, 1998; Anselin, 2001; Anselin, 2003):

1) Spatial lag model

$$Y_{it} = \rho W Y_{it} + X_{it}\beta + v_{it} \tag{4}$$

where the dependent variable Y_{it} is lagged spatially. It is added as an explanatory variable in the model.

2) Spatial Durbin model

$$Y_{it} = \rho W Y_{it} + X_{it}\beta + W X_{it}\varphi + v_{it} \tag{5}$$

where both dependent Y_{it} and selected explanatory X_{it} variables are spatially lagged and added in the right-hand side of the model.

Eqs. (4) and (5) are very unusual, because they posit the dependent variable as an explanatory variable. If the value of this variable for a municipality is determined in part by its neighbors, then equilibrium will occur as a function of some existing spatial or social interaction process between the locations (Anselin et al., 2008). This might be justified in either theoretical or in practical terms, because deforestation may be a phenomenon that occurs as an interactive factor—the space being determined according to the availability and accessibility of the resource to the economic agents involved. Such models are gaining enormous popularity in the literature for the evaluation of similar situations in which social or spatial interactions exist (see Brueckner, 2003 and Glaeser et al., 2002).

We used spatial data at the level of the municipality. These data contain important information about the interactions that occur between the spatial units. If these interactions are significant in such a way that the result in one spatial unit affects the outcome in neighboring spatial units, then the data are considered to be spatially autocorrelated. The presence of spatial autocorrelation violates the assumption of linear regression models, that observations are independent.

Spatial dependence, according to Anselin (1988) and Anselin and Bera (1998), can make the OLS estimators inconsistent and/or inefficient. However, according to Anselin (1995), spatial dependence can be incorporated into linear regression models in two ways: (1) through the construction of new variables, both for the dependent variable and for the explanatory variables and error terms of the model, that incorporate spatial dependence as a weighted average of the values of the neighbors; and (2) by using spatial autoregressive error terms. This study followed the first suggestion, adding variables to the model to mitigate the consequences of spatial dependence. First, we incorporated a spatial lag in the dependent variable. Then, we incorporated spatial lags both in the dependent variable and in the *openness to trade* variables.

5. Results

The results of the first estimations are presented in Table 2. The results of the regressions consider two types of models: one considers all the products in the exports and imports (*Openness 1*), the other, only exports and import of primary products (*Openness 2*).[17] The purpose of testing different measures of openness to trade is to verify the influence of only primary products on deforestation. In 2000, exports of primary products accounted for 53% of total exports; by 2010, primary products accounted for 77% of the total. Imports fluctuated less in the period: in 2000, 20% of imports were primary products and, in 2010, 23%. Therefore, non-primary products account for the preponderance of imports.

In each model, the results in Table 2 show estimates of regression by POOLS, fixed effect and random effect. Estimates of models with

[16] Other questions could be posed—for instance, what would be the effect on deforestation if all municipalities behaved similarly to the average statewide level of openness to trade?

[17] The primary products include products of animal, vegetable, and mineral origin.

Table 2
Panel regressions.

Independent variables	(1) All products POOLS	(1) All products Fixed effects	(1) All products Random effects	(2) Primary products POOLS	(2) Primary products Fixed effects	(2) Primary products Random effects
Constant	0.0001	−0.0001	0.0000	0.0001	−0.0001	0.0000
	(0.0068)	(0.0011)	(0.0256)	(0.0068)	(0.0011)	(0.0256)
Openness (1)	0.0175**	0.0001	0.0015			
	(0.0086)	(0.0022)	(0.0022)			
Openness (2)				0.0007	0.0033*	0.0018
				(0.0076)	(0.0022)	(0.0021)
GDP pc.	−0.1093***	−0.0091***	−0.0109***	−0.1042***	−0.0089***	−0.0106***
	(0.0101)	(0.0034)	(0.0039)	(0.0098)	(0.0035)	(0.0040)
Soybeans	0.1255***	0.0297**	0.0342***	0.1246***	0.0302**	0.0346***
	(0.0134)	(0.0140)	(0.0134)	(0.0134)	(0.0141)	(0.0134)
Cattle	0.7054***	0.1700***	0.2840***	0.7055***	0.1695***	0.2836***
	(0.0165)	(0.0156)	(0.0062)	(0.0165)	(0.0157)	(0.0267)
Wood	0.1876***	0.0159**	0.0182***	0.1895***	0.0160**	0.0183***
	(0.0158)	(0.0069)	(0.0073)	(0.0158)	(0.0033)	(0.0073)
Non-wood	−0.0169**	0.0025	0.0011	−0.0168***	0.0024	0.0010
	(0.0051)	(0.0017)	(0.0029)	(0.0051)	(0.0069)	(0.0017)
Settlement	0.0475***	0.0005	−0.0020	0.0476***	0.0004	−0.0021
	(0.0098)	(0.0017)	(0.0018)	(0.0098)	(0.0017)	(0.0022)
Prop. rights ind.	−0.0415***	0.0060**	0.0046	−0.0415***	0.0061**	0.0046
	(0.0042)	(0.0030)	(0.0035)	(0.0042)	(0.0031)	(0.0035)
Federal p. areas	0.0498***	−2.7321***	0.0634	0.0493***	−2.7320***	0.0633
	(0.0106)	(0.8931)	(0.0992)	(0.0107)	(0.8940)	(0.0992)
State p. areas	−0.0275***	−4.5992***	−0.2462***	−0.0255***	−4.6020***	−0.2460***
	(0.0073)	(0.4027)	(0.0684)	(0.0073)	(0.4026)	(0.0685)
Indigenous areas	0.0373***	−2.3606*	0.1281*	0.0370***	−2.3474*	0.1281*
	(0.0091)	(1.9798)	(0.0785)	(0.0091)	(1.9785)	(0.0256)
N	8602			8602		
R^2	0.5979	0.4072	0.3482	0.5976	0.4074	0.3474
Hausman	2801.51***			2804.83***		

Note: R^2 adjusted (Pooled) and R^2 *within* (fixed effects and random effects models). Robust standard errors are reported in parentheses.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

different indicators of openness to trade are identical in sign, though different in magnitude. In general, the estimates for all variables show the expected signs. However, some variables have opposite signs in different methods. We expected that increased openness to trade would raise the cost of deforestation, taking into account the increase in products to be exported. Controlling for the characteristics of the municipalities, openness to trade is directly related to deforestation and more intense and significant for primary products than for all products. This makes sense, since exports of primary products grew more than 600% in the period, and increased the proportion of total exports from 53% to 77%. Imports of primary products grew less in this period (about 300%).

The Hausman test suggests that the estimates by fixed effects are consistent in relation to random effects. The results for the other variables of the fixed effects regressions indicate that the GDP per capita contributes to reducing deforestation. Between 2000 and 2009 the value added of the agricultural sector of the Amazon region remained around 16%, while the share of value added of the services sector grew from 50% to 60%. The negative relationship between GDP per capita and deforestation is expected, and indicates that as the economy becomes more service-intensive, deforestation will decrease.

Estimates by fixed effects also indicate that soybean production, cattle ranching, and timbering contribute significantly to increased deforestation as the agricultural frontier advances into the Amazon rainforest.[18] The number of settlements has a positive, but not a significant, effect on deforestation. The indicator of property rights is positively associated with deforestation. This result is expected, since this indicator measures the level of uncertainty with respect to property rights. This result may also suggest that other potential issues, such as land conflicts, measured by the property rights indicator as well, contribute to increased deforestation.

The variables of *conservation areas* and *indigenous areas* are positively and significantly associated with a reduction in deforestation. This result is consistent with the idea that the legal establishment of protected areas and areas of exclusive use by the indigenous population is an important impediment to deforestation.

The economic variables used to explain deforestation, especially openness to trade and GDP per capita, can potentially generate endogenous effects. The results in Table 3 were constructed using two approaches to provide alternatives on initial estimates without controlling for endogeneity: instrumental variable (IV) and GMM. The estimations were carried out considering (1) the indicator of openness to trade with all products and (2) the indicator of openness to trade with only primary products. The values of the estimates for the two specifications were very close. The fixed effects regressions with IV use climate variables and the variables of status of property rights as multiple instruments for openness to trade and GDP per capita.

The F test indicates that the instruments are strongly correlated with the endogenous variables. The signs of the results obtained using instrumental variables with those obtained only by fixed effects (Table 2) are all the same. The main difference is that the *openness to trade* variable for all products becomes significant at 10%, the same level of significance of this variable considering only primary products. The relationship between GDP per capita and deforestation remains negative in the "primary products" scenario, but more intense. The variables that measure the effect of the expansion of the agricultural frontier toward the Amazon rainforest also have a stronger positive relationship with

[18] Some authors argue that the production of agricultural commodities on a large scale has increased so sharply in the Amazon region since the 1990s because of high international prices for soybeans (Brandão et al., 2006; Diniz et al., 2009). The domestic and international prices of commodities might be important variables to study; however, because of the high transaction costs, especially transportation, that the region faces, we opted not to use them in this study.

Table 3
Panel regressions with FE using IV and GMM.

Independent variables	(1) All products		(2) Primary products	
	IV[1]	GMM[2]	IV[1]	GMM[2]
Constant	−0.0001	0.0000	−0.0001	0.0000
	(0.0015)	(0.0005)	(0.0015)	(0.0005)
Deforestation (t − 1)		0.7899***		0.7901***
		(0.0070)		(0.0070)
Openness (1)	0.0889*	0.0014**		
	(0.0517)	(0.0014)		
Openness (2)			0.0819*	0.0012*
			(0.0446)	(0.00)
GDP pc.	−0.2416***	−0.0006***	−0.2373***	−0.0007***
	(0.0401)	(0.0027)	(0.0393)	(0.0027)
Soybeans	0.1242**	0.0205	0.1195***	0.0205
	(0.0195)	(0.0059)	(0.0197)	(0.0059)
Cattle	0.1832***	0.0225***	0.1843***	0.0225***
	(0.0100)	(0.0044)	(0.0101)	(0.0045)
Wood	0.0253***	0.0015	0.0255***	0.0015
	(0.0050)	(0.0024)	(0.0050)	(0.0024)
Non-wood	0.0045	0.0024	0.0052	0.0024
	(0.0035)	(0.0023)	(0.0036)	(0.0023)
Settlement	0.0016	0.0003	0.0019	0.0003
	(0.0017)	(0.0007)	(0.0018)	(0.0007)
Prop. rights ind.		0.0036***		0.0036***
		(0.0021)		(0.0021)
Federal p. areas	−3.1280***	−0.0199	−3.0477***	−0.0198
	(0.3272)	(0.0079)	(0.3226)	(0.0079)
State p. areas	−4.2759***	−0.3915	−4.2815***	−0.3903***
	(0.1773)	(0.0277)	(0.1757)	(0.0277)
Indigenous areas	−4.0592***	0.3168***	−4.0905***	0.3161***
	(1.0937)	(0.0137)	(1.0951)	(0.0137)
N	8602	7820	8062	7820
F test of instruments	238.62***		238.64***	
Sargan test of overidentifying restrictions		540.95***		540.76***
R^2	0.0183	0.3299	0.0183	0.2886

Note.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.
[1] The climate (temperature and rainfall) and land tenure status (landowner, tenant and squatter) variables are used as multiple instruments for openness and per capita GDP.
[2] GMM indicates the models estimated by difference GMM. Openness and per capita GDP are treated as endogenous and instrumented within the model. Rest of variables are treated as exogenous.

Table 4
Panel regressions with FE using GMM.*

Independent variables	(1) All products	(2) Primary products
Constant	0.0000	0.0000
	(0.0005)	(0.0005)
Deforestation (t − 1)	0.8885***	0.8788***
	(0.0060)	(0.0061)
Openness (1)	0.0030**	
	(0.0015)	
Openness (2)		0.016
		(0.0013)
GDP pc.	0.0245***	0.0199***
	(0.0030)	(0.0029)
Soybeans	0.0008	−0.0039
	(0.0030)	(0.0029)
Cattle	−0.0202***	−0.0181***
	(0.0047)	(0.0047)
Wood	0.0035	0.0028
	(0.0025)	(0.0025)
Non-wood	−0.0020	−0.0027
	(0.0025)	(0.0025)
Settlement	−0.0004	0.0001
	(0.0007)	(0.0007)
Landowner	−0.0195***	−0.0201***
	(0.0037)	(0.0037)
Tenant	−0.0023	−0.0018
	(0.0017)	(0.0017)
Squatter	0.0050**	0.0047
	(0.0020)	(0.0020)
Federal p. areas	−0.0028	−0.0016
	(0.0079)	(0.0080)
State p. areas	−0.0084	−0.0242***
	(0.0059)	(0.0071)
Indigenous areas	0.0847***	0.0823***
	(0.0101)	(0.0103)
Temperature	−0.0341***	−0.0259***
	(0.0050)	(0.0049)
Rainfall	0.0998***	0.1220***
	(0.0081)	(0.0088)
Sargan test of overidentifying restrictions	1042.9***	1072.8***y
N	7820	7820

Note.
The models are estimated by difference GMM. Openness and per capita GDP are treated as endogenous and instrumented within the model. Rest of variables are treated as exogenous.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

deforestation in the "primary products" (soy, cattle, and wood) estimation, while the federal conservation areas and indigenous areas have stronger negative relationship with deforestation.

GMM estimation uses difference and other instruments in relation to previous estimations, rather than in relation to fixed effects, which can make comparison between the results of GMM and fixed effects with IV unsuitable. However, the use of different approaches can generate other perspectives and bring some robustness to the results. In this case, the models include past deforestation as a control. This variable is significant and positively correlated with the current deforestation in both specifications. The GMM estimations also include the indicator of property rights drawn from the estimations by IV, since this indicator is constructed using the variable status of property rights. Comparing these estimates with those obtained by fixed effects with IV, one can observe that, except for *indigenous areas*, the coefficients have the same signs. Overall, the coefficients have lower magnitudes, and *soybeans*, *timber*, *federal*- and *state protected areas* area no longer significant, except for state protected areas in the specification with openness to trade with primary products. The Sargan test of overidentifying restrictions does reject instrument validity, but it does indicate that the results should be viewed with caution.

To improve upon the results of the GMM estimation, other specifications were performed. The estimates in Table 4 again consider the two possibilities with respect to the measure of openness to trade, both for all products and for primary products, and incorporate variables related to property rights, including the number of establishments operated by squatters, and climatic variables. *Past deforestation* correlates positively and significantly with current deforestation. *Openness to trade* has a positive sign, but is significant only in the model for all products. Compared to previous estimations, *GDP per capita* and *cattle* have opposite signs. *Soybeans* are not statistically significant in this model. With regard to *property rights*, land ownership contributes to reduced deforestation. This result is expected, since ownership is related to a more sustainable use of land, and tends to reduce disputes (e.g., violence) that result in deforestation. On the other hand, squatting tends to increase deforestation, but this effect is significant only in the model with openness to trade to all products. The coefficients for deforestation in indigenous areas were positive. The estimates also suggest that higher temperatures reduce deforestation and higher precipitation increases deforestation.

The results presented so far were based on data from all the municipalities of Legal Amazonia. However, not all municipalities of this region are involved in international trade. In fact, less than a third of the municipalities are involved in international trade. Table 5 shows the estimation results by fixed effects only and fixed effects with instrumental variables in the sample considering only the municipalities that are involved in trade. Another part of the table shows the results

Table 5
Panel regressions with FE using IV — tradable municipalities.

	(1) All products		(2) Primary products	
Independent variables	FE[1]	IV[2]	FE[1]	IV[2]
Constant	0.0000	0.0000	0.0000	0.0000
	(0.0024)	(0.0029)	(0.0000)	(0.0031)
Openness (1)	−0.0022	−0.0380		
	(0.0043)	(0.1041)		
Openness (2)			−0.0071*	−0.0958
			(0.0040)	(0.1005)
GDP pc.	0.0015	−0.2688	0.0148	−0.2651
	(0.0081)	(0.1842)	(0.0091)	(0.1659)
Soybeans	0.0501***	0.1136***	0.0548***	0.1265***
	(0.0226)	(0.0387)	(0.0227)	(0.0425)
Cattle	0.2528***	0.2657***	0.2574***	0.2548***
	(0.0321)	(0.0192)	(0.0345)	(0.0229)
Wood	0.0309***	0.0439***	0.0291***	0.0446***
	(0.0118)	(0.0115)	(0.0113)	(0.0119)
Non-wood	−0.0029	−0.0088	−0.0030	−0.0154
	(0.0046)	(0.0108)	(0.0042)	(0.0126)
Settlement	−0.0026	−0.0018	−0.0024	−0.0040
	(0.0043)	(0.0038)	(0.0046)	(0.0047)
Prop. rights ind.	0.0191***		0.0133**	
	(0.0064)		(0.0061)	
Federal p. areas	0.3406***	0.3356***	0.4030***	0.3378***
	(0.0857)	(0.0393)	(0.1171)	(0.0417)
State p. areas	−0.1244***	−0.2724***	−0.1499***	−0.2694***
	(0.0317)	(0.0875)	(0.0415)	(0.0928)
Indigenous areas	0.1288**	0.1149***	0.4436***	0.1150***
	(0.0668)	(0.0313)	(0.1106)	(0.0332)
N	2335		2055	
F test of instruments		146.85***		130.40^{***y}
R^2	0.3222	0.2651	0.3224	0.2535

Note.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.
1 Robust standard errors are reported in parentheses.
2 The climate (temperature and rainfall) and land tenure status (landowner, tenant and squatter) variables are used as multiple instruments for openness and per capita GDP.

considering the municipalities that trade only primary products. In this case, the estimates were also made using fixed effects and fixed effects with instrumental variables. Surprisingly, the estimates of the variables of openness to trade had negative signs. Regarding this variable, only the estimate by fixed effects in the sample considering only the municipalities that are involved in trade the coefficient *openness* is significant at 10% level. Controlling for the characteristics of the municipalities that participate in trade, a greater degree of openness could reduce deforestation. The elimination of the interaction with the municipalities that do not conduct trade indicates that non-trading municipalities may not be directly related to deforestation. International trade that has the potential to generate deforestation may be related to interactions between the trading and the non-trading municipalities.[19]

In Table 5, the estimates of two specifications have the same signs and similar magnitudes overall. In relation to the estimates of the models without sample restraints (Tables 2 and 3), we found the same signals and significance level for *soybeans*, *cattle* and *wood*. The *property rights indicator* has the same relation to deforestation, but it is more intense. Federal protected areas and indigenous areas have opposite signs.

The last set of regressions was performed to control for possible spatial correlation based on the models and specifications previously considered. The most intuitive spatial interaction in the specification of the models is the spatial lag. Deforestation is a phenomenon that may occur due to economic factors, institutional characteristics, and political motivations, as we have seen so far. However, the fact that there are few mechanisms for effective control of deforestation in the Amazon region promotes spillover effects. The mere fact that a given municipality is clearing can motivate the neighboring municipality do the same thing. If this phenomenon occurs, then there is the possibility of the presence of spatial autocorrelation, and controls to mitigate their effects should be incorporated into the model.[20]

Table 6 shows the estimation results by adding the spatial lag of deforestation as an explanatory variable. The purpose of including this variable is to control for deforestation in neighboring municipalities. This variable is correlated positively and significantly with deforestation, which suggests that deforestation in neighboring municipalities contributes to deforestation via effects of spatial spillovers. The other variables—openness to trade for all products and in relation to primary products—have signs similar to those of previous estimates by fixed effects and by fixed effects with instrumental variables in both specifications, *soybeans*, *cattle* and *wood* continue to show positive signs, but *wood* is not significant in the model with openness to trade for primary products. The *property rights indicator* suggests that insecurity and other features of property rights contribute significantly to deforestation. Deforestation is negatively associated with conservation areas and indigenous areas.

Table 7 shows the results of the models in Table 6, now confined to the sample of municipalities that are involved in foreign trade.[21] The variables of *openness to trade* are not significant, as they are in the estimations without spatial control (Table 5). The spatial lag of deforestation has a positive and significant coefficient. One last possibility was tested by including not only the spatial lag of deforestation, but also the spatial lag of openness to trade (Table 8). The goal in this case was to determine how the estimates change when controlling for openness in neighboring municipalities. The result suggests a negative relationship between openness to trade and deforestation in a neighboring municipality, but only with regard to the trade of primary products. Some linked competition effect among the primary activities of the municipalities might be responsible for this result. Deforestation in neighboring municipalities exerts a positive influence on deforestation in this estimation, as in previous estimations, but more intensely.

Comparing the results of Tables 7 and 8, the *openness to trade* and *property rights* variables have consistent signs and significance levels. *Soybeans*, *cattle*, and *timber* have the same relationship with deforestation, but the correlation is less intense. *Conservation areas* and *indigenous areas* are both negatively correlated with deforestation (Table 8), and have better-defined relationships when controlling for spatial effects on openness to trade.

6. Summary and Concluding Remarks

The objective of this study was to investigate the main determinants of deforestation in the Amazon region. For this, panel data information from 2000 to 2010 for 782 municipalities in the Amazon were used. The main parameters used to understand the dynamics of deforestation were economic and political/institutional issues in the region. The relationship between openness to trade and deforestation was estimated using two different specifications: one assessed openness to trade of all possible products; the other assessed openness to trade of primary products only. Alternative estimations were performed that excluded

[19] Moreover, the reduction of the sample may create inconsistent coefficients due to selection bias.

[20] Fig. 3 illustrates the LISA statistics (Local Moran) of deforestation for 2000 and 2010. The maps show significant clusters that have significant spatial autocorrelation at the local level. We can highlight two predominant local clusters in both years: (1) high-high: a cluster that covers a large part of Pará and northern Mato Grosso. This suggests that municipalities that also present high rates of deforestation are surrounded by municipalities that also present high rates of deforestation; and (2) low-low: a cluster that represents parts of Amazonas and parts of Pará, and almost all regions of Amapá and Tocantins. This result was achieved using k-nearest neighbors spatial weight matrix ($k = 10$). We tested tree possibilities: $k = 5$, $k = 10$ and $k = 15$, and the results were very similar.

[21] We did not consider the spatial lag of openness to trade in the model with only trading municipalities since the spatial interactions in this measure are poorly evaluated by the restricted sample.

Table 6
Spatial panel regressions with FE using IV and spatial lag of deforestation.

Independent variables	(1) All products		(2) Primary products	
	FE[1]	IV[2]	FE[1]	IV[2]
Constant	−0.0170	−0.0177	−0.0170	−0.0182
	(0.0013)	(12.1900)	(0.0013)	(0.0015)
Openness (1)	0.0027*	0.1410***		
	(0.0016)	(0.0477)		
Openness (2)			0.0004	0.1377***
			(0.0014)	(0.0429)
GDP pc.	−0.0031	−0.0824**	−0.0030	−0.0714**
	(0.0034)	(0.0368)	(0.0034)	(0.0371)
Soybeans	0.0228*	0.0412**	0.0230*	0.0303
	(0.0133)	(0.0184)	(0.0133)	(0.0196)
Cattle	0.1356***	0.1516***	0.1354***	0.1531***
	(0.0138)	(0.0088)	(0.0138)	(0.0090)
Wood	0.0048	0.0039	0.0049	0.0034
	(0.0063)	(0.0047)	(0.0063)	(0.0049)
Non-wood	0.0027**	0.0052*	0.0026**	0.0065**
	(0.0013)	(0.0032)	(0.0013)	(0.0034)
Settlement	−0.0022**	−0.0003	−0.0023	0.0003
	(0.0016)	(0.0016)	(0.0015)	(0.0017)
Prop. rights ind.	0.0069***		0.0070***	
	(0.0026)		(0.0026)	
Federal p. areas	−2.2416***	−2.4675***	−2.2393***	−2.3180***
	(0.5376)	(0.2957)	(0.5385)	(0.3017)
State p. areas	−3.7982***	−3.5651***	−3.8009***	−3.5449***
	(0.3546)	(0.1650)	(0.3547)	(0.1697)
Indigenous areas	−6.2494***	−7.3427***	−6.2381***	−7.5283***
	(1.7442)	(1.0035)	(1.7443)	(1.0404)
Spatial lag of deforestation	0.7659***	0.7958***	0.7652***	0.8219***
	(0.0402)	(0.0277)	(0.0403)	(0.0324)
N	8602		8602	
F test of instruments		251.11***		236.89***
R^2	0.5430	0.1163	0.5429	0.0650

Note.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.
[1] Robust standard errors are reported in parentheses.
[2] The climate (temperature and rainfall) and land tenure status (landowner, tenant and squatter) variables are used as multiple instruments for openness and per capita GDP.

Table 7
Spatial panel regressions with FE using IV and spatial lag of deforestation —.trading municipalities.

Independent variables	(1) All products		(2) Primary products	
	FE[1]	IV[2]	FE[1]	IV[2]
Constant	−0.1658	−0.1595	−0.2028	−0.1522
	(0.0212)	(0.0118)	(0.0252)	(0.0161)
Openness (1)	0.0017	−0.0941		
	(0.0035)	(0.0903)		
Openness (2)			−0.0024	−0.1038
			(0.0034)	(0.0902)
GDP pc.	0.0030	−0.1521	−0.0176**	−0.2047
	(0.0083)	(0.1621)	(0.0083)	(0.1520)
Soybeans	0.0402***	0.0900***	0.0606***	0.1072***
	(0.0219)	(0.0345)	(0.0223)	(0.0396)
Cattle	0.2190***	0.2236***	0.2188***	0.2190***
	(0.0302)	(0.0165)	(0.0330)	(0.0194)
Wood	0.0231**	0.0325***	0.0220**	0.0352***
	(0.0112)	(0.0102)	(0.0107)	(0.0110)
Non-wood	−0.0012	−0.0106	−0.0014	−0.0138
	(0.0043)	(0.0095)	(0.0039)	(0.0116)
Settlement	−0.0049	−0.0054	−0.0049	−0.0067
	(0.0040)	(0.0034)	(0.0044)	(0.0041)
Prop. rights ind.	0.0092*		0.0080*	
	(0.0055)		(0.0050)	
Federal p. areas	−0.0027	0.0096	−0.0853	0.0251
	(0.0730)	(0.0431)	(0.0966)	(0.0519)
State p. areas	−0.0922***	−0.2181***	−0.1060*	−0.2153***
	(0.0357)	(0.0785)	(0.0585)	(0.0858)
Indigenous areas	0.1437***	0.1308***	0.3914***	0.1304***
	(0.0519)	(0.0280)	(0.0922)	(0.0306)
Spatial lag of deforestation	0.6390***	0.6147***	0.6353***	0.5868***
	(0.0803)	(0.0443)	(0.0784)	(0.0611)
N	2335		2055	
F test of instruments		160.81***		132.21***
R^2	0.4818	0.4507	0.4816	0.4512

Note.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.
[1] Robust standard errors are reported in parentheses.
[2] The climate (temperature and rainfall) and land tenure status (landowner, tenant and squatter) variables are used as multiple instruments for openness and per capita GDP.

municipalities not involved in international trade. Another indicator was created to measure the relationship between property rights and deforestation.

The possibility of international trade can generate economic incentives with significant impacts on tropical forests. The expansion of the agricultural frontier toward the forest regions, mainly associated with the production of soybeans and livestock, is a movement that reflects the potential increase in profitability of these activities, and tends to be accompanied by openness to trade. The empirical evidence obtained indicates that the expansion of cattle ranching and soybean farming significantly increases deforestation. This indicates that decisions about land use directly determine the levels of both production and deforestation. The possibility of trade with foreign countries, in turn, also affects the allocation decisions of land use. The results indicate that openness to trade causes the rate of deforestation to increase.

The insecurity of property rights in the region is a second factor contributing to deforestation. Where boundaries are ill-defined and unprotected, there is often encroachment. Indigenous landowners, even protected by law, have little recourse against illegal timbering, and deforestation is a common result. Legal and well-defined initiatives designed to conserve indigenous lands generate the opposite effect on deforestation: the more such areas are protected, the less deforestation is seen.

We have seen that soybean production, cattle ranching, and openness to trade are directly or indirectly related to deforestation. The economic incentives for expansion are compelling, unless they are countered by disincentives. Initiatives observed by some private companies in the Amazon region prevent products originating from the conversion of forest areas into agricultural use from being purchased and marketed. The expansion of such initiatives could be supported by a requirement that a certificate of origin be applied to Brazilian products, whether meat, soybeans, or timber. A recent study by Gibbs et al. (2015) showed that since the Soy Moratorium took effect in 2006, only a small area of soil expansion in the Brazilian Amazon has occurred in newly deforested areas; thus, the moratorium has to some extent achieved its goal.

In addition, Assunçao et al. (2015) reported that in 2004 the launch of plan for the prevention and control of deforestation integrated action across government institutions and introduced procedures for monitoring, environmental control, and territorial management. Later, in 2008, new policy measures targeted municipalities with higher rates of deforestation were introduced in most of all states of Amazon region.

Income transfer policy could be another solution, although its effectiveness is unpredictable. One such initiative related to conservation policy is a cash-transfer program called Bolsa Floresta, which started in 2007 and has benefited almost 8,500 families living in forests that are protected by law. Families receive a monthly payment of 50 Reais (US$20) to stop deforestation. In order to be eligible to receive the grants, families must attend a two-day training program on environmental awareness and make a commitment to zero deforestation.[22] However, the effectiveness of this program can be compromised due to the lack of monitoring and enforcement.

[22] http://www.forestcarbonportal.com/project/forest-conservation-grant-fund-bolsa-floresta.

Table 8
Spatial panel regressions with FE using IV and spatial lags of deforestation, openness to trade (all products) and openness to trade (primary products).

	(1) All products		(2) Primary products	
Independent variables	FE[1]	IV[2]	FE[1]	IV[2]
Constant	−0.0170	−0.0176	−0.0169	−0.0175
	(0.0014)	(0.0015)	(0.0014)	(0.0016)
Openness (1)	0.0028*	0.1560***		
	(0.0016)	(0.0544)		
Openness (2)			0.0005	0.1611***
			(0.0015)	(0.0548)
GDP pc.	−0.0032	−0.0789**	−0.0030	−0.0648*
	(0.0034)	(0.0383)	(0.0034)	(0.0398)
Soybeans	0.0231*	0.0394**	0.0234*	0.0276
	(0.0133)	(0.0191)	(0.0133)	(0.0213)
Cattle	0.1354***	0.1517***	0.1352***	0.1539***
	(0.0138)	(0.0093)	(0.0138)	(0.0100)
Wood	0.0048*	0.0034	0.0049	0.0026
	(0.0063)	(0.0050)	(0.0063)	(0.0053)
Non-wood	0.0026*	0.0053	0.0026*	0.0070*
	(0.0013)	(0.0033)	(0.0013)	(0.0037)
Settlement	−0.0022	−0.0002	−0.0023**	0.0008
	(0.0015)	(0.0017)	(0.0015)	(0.0019)
Prop. rights ind.	0.0069***		0.0069***	
	(0.0026)		(0.0026)	
Federal p. areas	−2.2377***	−2.4403***	−2.2360***	−2.2529***
	(0.5398)	(0.3088)	(0.5412)	(0.3273)
State p. areas	−3.8005***	−3.5699***	−3.8035***	−3.5559***
	(0.3537)	(0.1728)	(0.3538)	(0.1833)
Indigenous areas	−6.2358***	−7.2836***	−6.2383***	−7.6265***
	(1.7413)	(1.0483)	(1.7447)	(1.1380)
Spatial lag of openness (1)	−0.0033	−0.0246***		
	(0.0097)	(0.0104)		
Spatial lag of openness (2)			−0.0029	−0.0388***
			(0.0094)	(0.0137)
Spatial lag of deforestation	0.7644***	0.7909***	0.7630***	0.8064***
	(0.0399)	(0.0286)	(0.0404)	(0.0331)
N	8602		8602	
F test of instruments		228.97***		202.38***
R^2	0.5431	0.0169	0.5429	0.0171

Note.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.
[1] Robust standard errors are reported in parentheses.
[2] The climate (temperature and rainfall) and land tenure status (landowner, tenant, and squatter) variables are used as multiple instruments for openness and per capita GDP.

Although agricultural credit policy is not the object of study of this work, a reduction in deforestation could be effected with the requirement of land demarcations and proof of more sustainable use of land as a criterion for granting credit. However, such initiatives cannot reach most establishments, since illegal practices related to the poor definition of rights of property are abundant. This being the case, expansion of the inspection, expediting, and resolving criminal cases related to land tenure and agrarian reform are desirable solutions.

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