Demand for Deforestation in the Amazon

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Abstract

This paper estimates the demand for deforestation on private properties in the Brazilian Amazon. To recover the demand, I exploit the fact that regional variation in transportation costs can be used to infer variation in the value of agricultural land relative to forested land. By rescaling these costs, I am able to value the difference between the land-uses in dollars per hectare. The results suggest that both Pigouvian taxes on agricultural land and payments to avoid deforestation (and carbon emissions) could have been effective in preserving the rainforest. Large landholders' behavior and the unequal distribution of land suggest that the policies are unlikely to reduce poverty and deforestation simultaneously. A carbon tax at the social cost of carbon could virtually eliminate the agricultural land in the Amazon.

JEL Classifications: Q2, Q57, Q58, L73, L78

KEYWORDS: Amazon, Brazil, deforestation, land use, quantile, instrumental variable, semi-parametric.

1 Introduction

The Amazon is the largest intact piece of contiguous tropical rainforest. It extends over nine countries of South America and occupies an area of 6.4 million square kilometers. It has an unusually rich amount of biodiversity and provides extensive carbon storage and water recycling services. For these reasons, its deforestation has attracted considerable attention over the last two decades. According to satellite images, approximately 15 percent of the Brazilian Amazon was deforested by 2010, and the average amount of deforestation between 1991 and 2010 was 16.6 thousands square kilometers annually (larger than the area of the state of Connecticut in USA) [INPE (2010)].

In this paper I estimate the demand for deforestation on private properties in the Brazilian Amazon. The demand function is defined as the amount of deforested area as a function of the difference between the private value of the agricultural and forested land. I am interested in this demand because it can be used to study multiple policy interventions with the ultimate goal of preventing deforestation. Here I consider three possible policies: (a) payments for ecological services (PES), (b) Pigouvian taxes on agricultural land, and (c) quantitative limits on deforestation allowed on private properties.

There are several reasons why one may be interested in studying these policies. First, PES programs are incentive-based mechanisms involving direct payments to suppliers conditional on providing an environmental service [Wunder (2007)]. They have been seriously considered in recent years as a viable option to preserve the environment, especially when considering the payments for reduced emissions from deforestation and degradation (REDD+) agreements.[1] According to the Intergovernmental Panel on Climate Change (IPCC), deforestation and forest degradation are responsible for approximately 20 percent of the average global anthropogenic greenhouse gas emissions per year in the 1990s and for 10 percent in the last decade [IPCC (2007, 2013)]. Despite these facts, large-scale PES programs have not yet been adopted in the Brazilian Amazon. An evaluation of both the potential effectiveness and the potential costs of such programs are therefore in order. In the present paper, I study a specific type of PES program: payments to avoid deforestation. Although payments to replant forests are important, they are not considered here.

Second, Pigouvian taxes have also not been adopted in the Brazilian Amazon. They are defined as taxes levied on the production of negative externalities, such as emissions of carbon and biodi-

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[1]REDD+ is a carbon credit regime under negotiation in the United Nations Framework Convention on Climate Change (UNFCCC). Under this regime, countries with high emissions can pay to protect forests in developing nations, primarily tropical countries, and count the storage of carbon in protected forests in their overall carbon output.

versity loss. In cases where the measurement of the externalities is difficult, Pigouvian taxes can be directed to the adoption of particular land uses. Here I consider taxes on agricultural land, which should have similar impacts to payments to avoid deforestation, except for the fact that farmers would have to bear the costs of preservation. Because payments and taxes are similar in the present context I lump them into one policy and refer to them simply as taxes - unless stated otherwise.

Third, the Brazilian government has implemented quantitative limits for land use. By law, landowners in the Amazon are obligated to keep 80 percent of their land in native forest. In spite of the evidence that this rule has not been fully enforced (see the discussion about legislation and penalties in Subsection 2.2), one might wonder how costly this policy would have been if it were perfectly enforced. To the best of my knowledge, no empirical study addressing these policies for the Brazilian Amazon in a unified and coherent framework currently exists.

The policies I consider should have substantial impacts on deforestation only if they are put in force for a long period of time. Because deforesting is costly, farmers are more likely to respond to persistent changes in private values than to temporary changes. Temporary taxes probably have negligible impacts on deforestation. My focus therefore is on permanent policies and on permanent effects, as opposed to transitional dynamics.[2]

To estimate the demand for deforestation I use a revealed preference approach and exploit the fact that regional variation in transportation costs can be used to infer variation in the value of agricultural land relative to forested land. To gain some intuition, imagine one farm located close to the port and another that is far away from the port. *Ceteris paribus*, as transportation costs increases, both the values of agricultural and forested land should decrease. Yet, if the value of the agricultural land is more affected by the transportation costs, its *relative* value should be reduced. As a result, one should expect less deforestation in the farm located away from the port than in the farm that is close to the port. Note that Pigouvian taxes intend to do the same: to reduce the relative value of agricultural land in order to reduce deforestation. Variation in transportation costs therefore can be exploited to infer how farmers would respond to taxes. By rescaling the transportation costs using local yields, I am able to value the difference between the land uses in dollars per hectare. The strategy I propose therefore is divided into two steps: first, I estimate the effects of transportation costs on deforestation, and second, I rescale these costs using local yields

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[2]See Berry (2011) for a discussion of the importance of distinguishing the short-run and the long-run land-use elasticities for biofuels policies; and Scott (2013) for a fully dynamic model of land-use for the U.S.. Paul Scott, Ted Rosenbaum and I are currently working on a structural dynamic model of land-use for the Amazon to estimate the impacts of commodity prices on deforestation.

to recover the demand function.[3]

One might wonder why not use the price of land instead of transportation costs to estimate the demand. Unfortunately, data on land prices available for the Brazilian Amazon do not distinguish the price of forested land from the price of agricultural land. As a result, variation in the observed *average* land price cannot be used to infer variation in the *relative* values. Another possibility would be to explore data on penalties for illegal deforestation. However, data on punishments are scarce. In addition, significant evidence that the legislation has not been fully enforced in the Amazon exists (see Subsection 2.2).[4]

Note that even if the data on land prices and on punishments were available, exploiting regional variation in transportation costs is appropriate to recover farmers' responses to permanent taxes because persistent changes in private values are likely to be captured by differences in transportation costs in a geographical cross-section. I therefore estimate the demand function combining the Brazilian transportation network of 2006 with the Brazilian Agricultural Census of 2006, which is the most recent and comprehensive data available for the agricultural sector in the country. I supplement the data with spatial information on important determinants of land use such as soil quality, topography, temperature and precipitation.

Because the three policies try to influence what farmers are doing with their land, I focus on landowners' choices *within* private properties. It makes little sense to tax (or pay for) land that no one owns; and the 80 percent rule does not apply to public land. Deforestation of public land is an important problem in the Amazon, but one that I must ignore here. I also split the sample into different farm sizes and run the analysis separately for each sub-group. Separating the groups allows for diminishing (or increasing) returns to agricultural land that may affect farmer's private valuations. It also may be informative for policy-makers. To the extent that policy makers may view payment programs as a way to reduce poverty, they may want to adjust the payments to small landholders.[5]

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[3]In principle, the relative value of agricultural land could increase with the transportation costs. I do not impose restrictions on the direction of the effect in the estimation procedure - all I need is that transportation costs has a differential impact on the private values. The first step of my strategy relates to a growing literature that estimates the impact of roads on deforestation. See Reis and Guzman (1992), Chomitz and Gray (1996), Pfaff (1999), Andersen et al. (2002), and Weinhold and Reis (2008). For a review of the literature see Nelson and Geoghegan (2002).

[4]A third approach would measure the value of alternative land uses by means of "engineering/costing models." One can calculate the values of the land uses from the revenues and costs of the different alternatives of a representative farm [Börner et al. (2010)]. Although the procedure provides valuable information, it may be potentially limited in recovering the actual preferences of farmers because there may be private benefits or costs (some possibly non-pecuniary) to alternative land uses that the researcher is unaware of. See Stavins (1999) for a discussion.

[5]Affecting decisions within farmland is an important way to promote conservation, considering that the properties occupy about 18 percent of the Amazon, according to the Brazilian Agricultural Census of 2006. More importantly, the deforestation has been more intense in the states of the South Amazon (the states of Rondônia and Mato Grosso,

The main policy implications from the estimated demand function are the following: first, taxes could have been effective in avoiding deforestation if they were implemented and fully enforced. For example, in response to a Pigouvian tax of US$ 40 per hectare per year on agricultural land, farmers would be willing to maintain 80 percent forest coverage on private properties as opposed to the 40 percent forest coverage observed in the data. The 40 percent difference corresponds to approximately 30 million hectares. To have a sense of magnitude, farmers' average gross revenue per hectare in the Amazon in 2006 was US$ 120/ha. If their profit margins were approximately 10 percent of the gross revenues, it should be no surprise that many farmers would not be willing to produce with such a tax.[6]

Second, the policies should *not* target the small landholders. The fact that large landholders are the most responsive to taxes/payments, together with the extremely unequal distribution of land in the Amazon, suggests that payments unlikely reduce local poverty and deforestation simultaneously.

Third, the existing legislation (the 80 percent rule) could have been expensive for local farmers if it were perfectly enforced. It could have resulted in, at least, US$ 4.7 billion per year of farmers' lost surplus. A tax of US$ 40/ha could also result in 80 percent of forest cover, but it would have been roughly ten times less expensive: farmers' lost surplus would have been approximately US$ 484 million per year - provided the tax revenues were redistributed to them.[7] The 80 percent rule would have been more expensive than taxes because the more productive farms would have to use less land for agriculture and, so, would have forgone more profits. In addition to the differences in costs, the geographic pattern also would be different: deforestation under taxes would be more concentrated in the South Amazon, arguably the most productive area. As a result, the forests in the center regions of the rainforest would have been less fragmented, which may be advantageous from a biodiversity point of view. Payments of US$ 40/ha would have the same impact as taxes - but would require US$ 2.5 billion per year of transfers to farmers (approximately 1.4 percent of the Brazilian federal budget for 2006). As far as I am aware, this is the first study quantifying these costs for the Amazon.[8]

Finally, by combining the estimated demand for deforestation with the geographic distribution of the carbon stock in Brazil [Baccini et al. (2012)], I obtain a "supply of avoided emissions." If a

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see Section 2) where private properties occupy about 45 percent of their total area.

[6] The standard deviation of the gross revenues in 2006 was US$ 560/ha. The high dispersion may help explain why a considerable amount of land might still be farmed under the US$ 40/ha tax. Note that, instead of a perfectly enforced tax, one may interpret the US$ 40/ha as the expected tax that farmers would pay.

[7] Tax revenues would have been approximately US$ 627 million per year (0.35 percent of the Brazilian federal budget for 2006).

[8] A perfectly targeted policy paying US$ 40/ha *only* to those who would deforest their lands, and *not* paying those who would *not* deforest, would have cost almost half the non-targeted program: US$ 1.2 billion per year.

carbon tax of (or a REDD+ program paying) US\$ 1 per ton of CO_2 per year were implemented, farmers would be willing to avoid the emissions of approximately 4 billion tons of carbon (by avoiding deforestation). The avoided emissions correspond to approximately 3 years of worldwide emissions from land-use change [IPCC (2007)]. A carbon tax at the social cost of carbon - US\$ 21/tCO_2 for 2010 (2007\$) [Greenstone et al. (2011)] - could virtually eliminate the agricultural land in the Amazon.

2 Background

2.1 Brief History of the Occupation of the Amazon

Before the 1960s, the Amazon was barely occupied. Open access to forestry was typical and the local economy was based on subsistence and a few extraction activities: mainly rubber and Brazilian nuts. Most of the municipal seats were established by late 1800s and early 1900s as a result of these activities.[9] During the 1960s and 1970s, however, the military dictatorship promoted the occupation of the region. The explicit objective was to secure the national borders and to integrate the region. They constructed hydroelectric facilities, mining, ports, and around 60,000 km of roads [Andersen and Reis (1997)]. The first overland connection between the Amazonia and the rest of the country was completed in 1964: a highway linking Belem, an Amazonian state capital, and Brasilia, the country's capital city located in the central region (See figure 1 in Subsection 2.3). During the 1980s, the economic recession and hyperinflation led the government to cut investments. After the 1990s, ecological concerns shaped the policies in the Amazon. IBAMA (Brazilian Environment Protection Agency) was created in 1989 to monitor and enforce environmental policies. In 1996, the required share of forest cover on private land in the Amazon increased from 50 percent to 80 percent.

2.2 Legislation and Penalties

If a farmer wants to clear a fraction of her land, she needs to hold many licenses and authorizations, including a detailed plan of management that must be approved by IBAMA. The requirements are costly, time consuming and may take several months to be approved [Hirakuri (2003)]. Sanctions for forest-related violations include fines ranging from US\$ 2,300 to US\$ 23,000 per hectare, the seizure of products and equipments, and the suspension of activities. The fines are extremely costly to farmers in view of their average gross revenue per hectare, which was US\$ 120/ha according to

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[9]Source: http://cidades.ibge.gov.br/xtras/home.php

the Agricultural Census of 2006.

However, there is evidence that the legislation has not been fully enforced. For example, between 2005 and 2009, IBAMA applied 24,161 fines totalling about US$ 7.34 million, but the revenues collected from these fines were only 0.6 percent of the total value [TCU (2009)]. Perhaps more importantly, the proportion of deforested area (according to the satellite images) that received fines was small before 2006: approximately 0.15 percent in 2003; 0.1 percent in 2004; 1.2 percent in 2005; and 7.9 percent in 2006. Furthermore, Brito and Barreto (2006) analyzed a sample of 55 court cases against environmental violations in the forest sector in the Pará state between 2000 and 2003 and found that only 2 percent of the offenders were criminally liable. Therefore, given the apparent small expected cost of punishment, one might expect farmers to slash-and-burn to clear the land without authorization.[10]

2.3   Transportation Network

Figures 1 and 2 present the transportation network in Brazil. The left panel of figure 1 shows the map of Brazil with the location of the Amazon rainforest and the names of the Amazonian states; the navigable rivers; and the main ports. Rivers have always been important in the Amazon, especially in the western region where they are the only option of transportation for the local population. The right panel of figure 1 presents the railroads and the Amazonian state capitals. Railroads are not very prevalent in the Brazilian territory, are concentrated in the southeast and are mainly directed to ports. The main ports in the country are also located in the southeast; the most important ports being the Port of Santos and the Port of Paranaguá. Not only is the infrastructure of these ports better, the roads linked to them are also of better quality than in the rest of the country, making them a better option than the ports in the north for exports.

Figure 2 shows, in the left panel, the location of roads distinguishing paved from unpaved roads. Most of the roads in the Amazon are unpaved (89 per cent according to the Ministry of Transport). The few paved roads in the region tend to connect the main state capitals. The right panel of figure 2 puts together the transportation network and the deforested area in 2006 according to satellite images. The spatial correlation between them can easily be seen. Most of the deforested area is concentrated in the southern and eastern parts of the Amazon, which is normally called the "Arc of Deforestation". Nepstad et al. (2001) documented that approximately two-thirds of the total

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[10]The proportion of deforested area that received fines has increased after 2006: 49 percent in 2007; 44 percent in 2008; 51 percent in 2009, and 24 percent in 2010 (based on information provided by Pedro Ferraz Cruz, from IBAMA, in a personal message sent on April 7, 2011). It seems to be the result of the increased government efforts to slowdown deforestation combined with the better use of satellite images. I plan to investigate in the future the impacts of the change in the monitoring efforts. See Assuncao et al (2012).
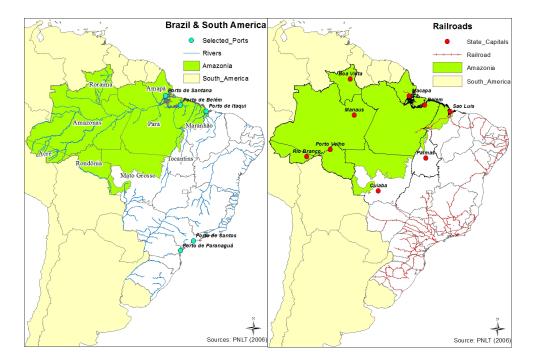
Figure 1: Transportation Network - Rivers and Railroads

Amazon deforestation between 1978 and 1994 occurred within 50 km of major paved highways.

2.4 Area Occupied

Private farmland occupies about 18 percent of the Amazon, but the proportion varies depending on the region: it occupies 45 percent of the *South Amazon*; 19 percent of the *Eastern Amazon*; and 4.5 percent of the *Western Amazon*. Conservation Units and Indigenous Reserves accounted for approximately 44 percent of the Amazon by 2010 [INPE (2010)]. A rough calculation therefore suggests that approximately 38 percent of the region is unprotected public land - that can still be occupied and claimed by squatters. Despite this fact, most farmers have their land titles (85 percent), and the proportion of farms with no land titles is higher among the small landholders (20 percent).[11]

Most of the private farmland is used for pasture (about 49 percent) and most of the cattle is used to produce beef. The area occupied by crops is only 10 percent. Its participation, however, has increased lately in the "Arc of Deforestation". Soybeans is the most important product (it occupies about 22 percent of the crop area), followed by corn (11 percent), manioc (11 percent), rice (8.4 percent) and beans (4 percent). Finally, forests occupy about 37 percent of the private land. Among

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[11]The *South Amazon* comprises the states of Rondônia and Mato Grosso; the *Eastern Amazon*, the states of Pará, Amapá, part of Tocantins and part of Maranhão; and the *Western Amazon*, the states of Amazonas, Acre and Roraima. See Figure 1. Small landholders in the present paper are those who own farms with less than 5 hectares.
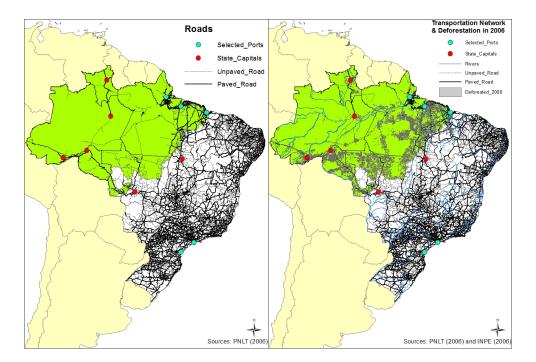
Figure 2: Transportation Network and Deforestation

the extraction of forest products, the most important in terms of the value of production in 2006 was açaí, an Amazonian fruit (41 percent), and timber (39 percent).[12]

3 Model and Estimation

Next, I present a simple stylized model to guide the empirical application. Before presenting the details of the model, a couple of remarks are in order. First, deforestation is defined here as the share of agricultural land on private properties. I assume the land was originally forested, so that clearing it for agriculture is equivalent to deforesting. The remaining area can be used for managed forest.[13]

Second, the available data is aggregated at the municipality level. It is not possible then to distinguish between a model in which farmers choose the share of agricultural land and a model in

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[12]Brazil has the largest number of cattle in the world (171 million cattle in 2006, of which approximately 35% were in the Amazon). It is the second largest producer of beef and is the largest beef exporter. Brazil also is the largest exporter of soybeans in the world (USDA, www.fas.usda.gov/psdonline/). Production of soybeans and corn are located mostly in the South Amazon and are directed to international markets. Manioc, rice and beans are consumed domestically, with manioc being more concentrated in pristine areas, possibly for subsistence. Açaí is primarily produced for domestic markets. The logging industry is located along the "Arc of Deforestation" and it directed 36 percent of its production (after processing) to international markets in 2009 [Pereira et al. (2010)].

[13]Although most of the deforestation took place in the past, transportation costs must have decreased over time as the transportation network evolved. The incentives to deforest in response to these costs must have increased over the years. As a result, if a farmer had cleared her land in the past, she would probably clear it in 2006 if she were to decide in that year.

which there is a continuum of farmers making binary choices. The typical exercise in the literature that estimates the impact of roads on deforestation assumes a binary choice model for landowners' decisions and aggregates their choices at the municipality level [Pfaff (1999)]. I follow the literature to make my procedure comparable to the existing papers and because the binary choice model is convenient to interpret the results.[14]

Next, I present the details of the model. Then, I proceed discussing the rescaling exercise and the identification strategy.

3.1 Model

Take a parcel of land i located at municipality m and that belongs to a farm of size s. Assume there is a continuum of such parcels, and for each one, the farmer is deciding whether or not to clear it for agriculture. Let P_{ims} be a vector with output and input farmgate prices and Z_{ims} be the vector of productivity shocks. Define $\Pi^a\left(P_{ims}, Z_{ims}\right)$ as the expected discounted present value of future profits obtained by using the parcel for agriculture, including the conversion costs, and $\Pi^f\left(P_{ims}, Z_{ims}\right)$ as the corresponding value obtained leaving the plot as managed forest. Let Y_{ims} equal one if the plot i is cleared and zero otherwise. Then:

$$Y_{ims} = 1\left\{\Pi^a\left(P_{ims}, Z_{ims}\right) > \Pi^f\left(P_{ims}, Z_{ims}\right)\right\},$$

where $1\left\{.\right\}$ is the indicator function.

The productivity shock is assumed to be the vector $Z_{ims} = \left(Z_m, U_m\left(s\right), \varepsilon^z_{ims}\right)$, where Z_m is a municipality-level vector of observed productivity shifters, such as soil quality and other agro climatic conditions; $U_m\left(s\right)$ is a municipality-level unobserved productivity shock; and ε^z_{ims} captures the farmer's unobserved idiosyncratic abilities, efforts and the deviations from Z_m and $U_m\left(s\right)$ within m. Because the empirical analysis is done separate for each farm size, it is possible to allow the unobservable $U_m\left(s\right)$ to be indexed by the size of the farm - which allows for a richer model than the usual municipality random effect model. I.e., a municipality may be good for agriculture for, say, large farms, but may not be as good for small landholders.

I assume farmers are price takers, that all production is sold in nearby markets or exported directly, and that a no-arbitrage condition holds. The assumptions imply that local prices are determined by the international price minus the transportation cost to the nearest port, i.e., $P_{ims} = \overline{P} - TC_{ims}$. The transportation cost TC_{ims} by its turn can be decomposed into TC_m and ε^t_{ims}.

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[14]The aggregated data also prevents me from considering local neighbor interactions. See, e.g., Alix-Garcia, Shapiro and Sims (2012).

The cost to transport a product from the municipal seat to the nearest port is denoted by TC_m; a proxy for this variable is observed in the data. The deviation of the farm's transportation cost to TC_m is denoted by ε^t_{ims}, is unobserved by the econometrician but is observed by the farmer.

Although the costs to transport different products may not be equal to each other, they should be proportional: all products use the same transportation network and reach the same ports (under the no-arbitrage condition). Therefore, the transportation costs of different products should be perfectly, or at least highly, collinear - which makes it difficult to separately identify their impacts on deforestation. I therefore proceed with a unique measurement of transportation costs to reflect differences in local prices. The exact proxy for TC_m is explained in Section 4.

The existing literature typically projects the difference between Π^a and Π^f on the municipal-level variables $(TC_m, Z_m, U_m(s))$ and collapses all individual heterogeneity into a single scalar ε_{ims}. In the present case, the model reduces to

$$Y_{ims} = 1\left\{ Z'_m \beta_s - \alpha_s TC_m + U_m(s) - \varepsilon_{ims} > 0 \right\},$$

where the coefficients can be different for different farm sizes. In addition, an extreme value distribution for ε_{ims} is typically imposed. The resulting logit model can be estimated after taking the differences of log shares as:

$$\log\left(\frac{Y_m(s)}{1 - Y_m(s)} \right) = Z'_m \beta_s - \alpha_s TC_m + U_m(s), \tag{1}$$

where $Y_m(s)$ is the share of agricultural land within farms of size s in municipality m.

Note that the size of the farm, s, is not an explanatory variable in equation (1). I do not attempt to explain deforestation by exogenously varying the size of the farms. Although the endogeneity of farm sizes has been extensively discussed in the literature, particularly in the literature that estimates impacts of cultivated agricultural area on rural productivity (see, e.g., Foster and Rosenzweig (2011) and the references cited therein), there is no problem of endogeneity of farm sizes when estimating equation (1).[15]

The typical exercise in the literature estimates equation (1) using OLS [Pfaff (1999)]. My procedure builds on the typical exercise, but improves upon it in three aspects. First, transportation costs are instrumented with straight-line distances to the main destinations, D_m, which addresses the potential endogeneity of roads and measurement errors in transportation costs. Second, I

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[15]To identify impacts of farm sizes on the profitability of farms in India, Foster and Rosenzweig (2011) make use of the fact that a substantial fraction of the households in their data divided and/or received inherited land because a parent died. This source of exogenous variation together with the panel data structure are exploited to handle the endogeneity of farm sizes.

use a quantile regression instead of a mean regression. Third, I relax functional form restrictions by dropping the logit assumption to check whether it may drive the results. In the next set of paragraphs, I expose the more flexible model I adopt. However, I leave for Subsection 3.3 a discussion of the reasons why transportation costs to the nearest port should be instrumented and under what conditions straight-line distances to the main destinations are expected to be valid instruments.

Weinhold and Reis' (2008) and Pfaff and Robalino's (2009) results suggest that the impact of roads on deforestation may depend on the level of the previously cleared area. Presumably, a highly deforested place must be so good for agriculture in terms of unobservables that transportation costs would have to increase considerably to affect the share of agricultural land. On the other hand, a preserved location may be so bad for agriculture that small increases in TC_m could substantially reduce deforestation. The impacts of roads therefore likely differ on the upper tail and on the lower tail of the distribution of deforestation (across municipalities). The relative value of the agricultural land also likely differs, which may affect the geographic pattern of land use from taxes. Some places may be more sensitive to taxes than others and, so, may face larger costs (lost surpluses) from taxes. The local differences may lead to non-trivial impacts on the aggregated costs of the policy interventions.

To allow transportation costs to affect the entire distribution of deforestation I therefore turn to a quantile model. Instead of estimating equation (1), I estimate:

$$\log\left(\frac{Y_m\left(s\right)}{1 - Y_m\left(s\right)}\right) = Z_m'\beta\left(U_m\left(s\right)\right) - \alpha\left(U_m\left(s\right)\right) \times TC_m, \tag{2}$$

where $U_m\left(s\right)$ is assumed to have a uniform distribution on $[0, 1]$ given the instruments, D_m. It is clear from the random coefficient representation in (2) that the coefficients can depend arbitrarily on both the farm size s and the quantile u. This flexibility relaxes the role of both the single-index restriction and the logit assumption in determining the shape of the demand for deforestation. I estimate equation (2) using the instrumental variable quantile regression estimator (IVQR) proposed by Chernozhukov and Hansen (2008). From now on, I change the notation slightly and denote the coefficients by $(\beta_{su}, \alpha_{su})$.

Next, I drop the logit assumption and estimate the semiparametric model:

$$G_s\left(Y_m\left(s\right), u\right) = Z_m'\beta_{su} - TC_m, \tag{3}$$

where the function $G_s\left(., u\right)$ is unknown. Because a normalization for the single-index is required, the coefficient on transportation cost is normalized to be minus one and the constant, to be zero.

The normalization is without loss as long as TC_m impacts the deforestation negatively. The semi-parametric quantile IV model (SPQIV) is estimated using the penalized sieve minimum distance estimator (PSMD) proposed by Chen and Pouzo (2012). The details of the estimator is explained in the Supplemental Material [Souza-Rodrigues (2013)].

Denote the distribution of ε_{ims} by $F_s = G_s^{-1}$. Then, the share of agricultural land in municipality m for farms of size s is given by:

$$Y_m(s) = F_s\left(Z_m'\beta_{su} - TC_m, u\right). \tag{4}$$

3.2 The Rescaling Exercise

The scale normalization in a binary choice model defines the unit in which the difference in the private values $\left(\Pi^a - \Pi^f\right)$ is measured. By fixing the coefficient of transportation cost to be minus one in (4), the estimated difference in private values is measured in the same units as TC_m, i.e., in dollars per ton of output transported. The normalization is useful: to evaluate how farmers would respond to a Pigouvian tax (measured in dollars per hectare) it is sufficient to rescale the tax value to dollars per ton of output transported so that the resulting change in the private values, $\left(\Pi^a - \Pi^f\right)$, is measured in dollars per ton of output transported.

Formally, denote by $q_m(s)$ the quantity (tons) of agricultural output sold per hectare for farms of size s in municipality m. The effect of raising the value of the forested area by US\$ t per hectare on farmers' land-use decision is then:

$$Y_m^t(s) = F_s\left(Z_m'\beta_{su} - TC_m - \frac{t}{q_m(s)}, u\right). \tag{5}$$

where $Y_m^t(s)$ is the counterfactual share of agricultural land. Equation (5) defines the *demand for deforestation* in this paper. The same reasoning can be applied to the logit model, even though it has the "wrong" normalization.[16]

The rescaling exercise has two potential problems that I discuss next: an aggregation problem and an endogeneity problem. Because the data is aggregated at the municipal level, the aggregation problem involves the choice of the products that may be considered in $q_m(s)$. The endogeneity problem refers to the fact that $q_m(s)$ itself may respond to TC_m.

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[16]In principle, observed variables other than TC_m could be used to fix the scale of the private values. But, to be useful, any such variable would have to satisfy the following requirements: (i) it must affect farmers' decision significantly, i.e., it must have a coefficient that is different from zero; and (ii) it must be measured in dollars in a way that can be converted into the right unit. None of the variables in Z_m in the data set satisfies the requirements. Note that the normalization in the logit model does not require TC_m to impact the deforestation negatively.

3.2.1   The Aggregation Problem

If the micro-data on farmers' decision level were available, I could assume that the cleared land is in its best private use and I could put the individual yields directly into (5). However, because the data is aggregated at the municipality level, and because there are hundreds of products being produced in the Amazon, some care is needed in defining the rescaling factor. I selected the most representative products in the Amazon and constructed two different productivity indices to check by how much the results were sensible to the indices. The first index is based on the production of beef and the yields of the most representative crops (those discussed in the Subsection 2.4). It is denoted by $q_m^{cp}(s)$. The second index, denoted by $q_m^c(s)$, only considers the main crops and ignores the pasture land. The weights in the indices are the proportions of the area utilized for each product.[17]

Different productivity indices are associated with different underlying multinomial choice models. The first index, $q_m^{cp}(s)$, is associated with a "fixed-proportions" model. The underlying assumption in this case is that once the land is cleared for agriculture, it is used in fixed proportions for pasture and for the main crops. The proportions are allowed to differ for different municipalities, but they are fixed within the municipality. It does not allow for flexible substitution patterns among the possible land-uses. If the importance of the substitution patterns is not central for the present problem the "fixed-proportions" model should provide a good estimate of the demand for deforestation.

The second index, $q_m^c(s)$, is associated with a "vertical" multinomial choice model: once the land is cleared for agriculture, it is used only for the representative crops. In this case, farmers do not substitute forests for pasture. The "vertical" model likely results in an upper bound on the demand for deforestation. To see why, note that because the production of beef is land-intensive, one should expect the first index, $q_m^{cp}(s)$, to be smaller than the second, $q_m^c(s)$ - as it is in the data. Furthermore, because $Y_m^t(s)$ is increasing in $q_m(s)$ - see equation (5) - the demand curve based on the "vertical" model should be above the demand curve based on the "fixed-proportions" model, and also should be above any demand curve that allows for rich substitution pattern between forests and pasture.

There is an essential difficulty in the present data set to recover flexible substitution patterns

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[17]Although bulk products and sacks must have the same transportation costs [Castro (2003)], transporting livestock and frozen meat are more expensive. According to the freight data, it is 30 percent more expensive to transport frozen meat than soybeans. For this reason, I increased the weight for the beef in the productivity index $q_m^{cp}(s)$ by 30 percent so that the transportation costs of all products are measured in terms of the costs to transport one ton of crops (see Supplemental Material).

among the land-uses within agricultural areas. In principle, the substitution patterns can be recovered by exploiting choice-specific variables that shift the value of each land-use independently of the value of the other options [Berry and Haile (2012)]. However, there is no variable satisfying such a requirement in the present data set. Although one might argue that it is still possible to estimate a parametric multinomial choice model in the absence of the choice-specific variables, the estimated model could be inconsistent with the underlying model associated with the productivity indices. And the indices are necessary to recover the demand for deforestation. For this reason, I opted for being agnostic in how the agricultural area is divided when estimating the impacts of TC_m on deforestation, and experimented with the different indices associated with the different multinomial models.

3.2.2 The Endogeneity Problem

The second potential problem refers to the fact that the local yields may be affected by changes in transportation costs. I regressed both productivity indices on the same set of explanatory variables and used the same set of instruments as in the land-use regressions and I found small nonsignificant impacts of TC_m (see the Supplemental Material). The elasticities are all reasonably close to zero. Farmers therefore seem to adjust the extensive margin (land-use), but not the intensive margin (production per hectare), in response to changes in transportation costs. The result is consistent with Roberts and Schlenker (2013). Using a world supply and demand model for grain crops, they find that almost all of the supply response to changes in commodity prices comes from an expansion of the cultivated area.

3.3 Identification Strategy

There are several reasons why one needs to instrument transportation costs. First, they are likely measured with an error. The proxy for transportation costs is defined here as the minimum unit cost (US\$/ton) to transport one ton of goods to the nearest port using the most cost-effective route. It is a common proxy used in the literature [Donaldson and Hornbeck (2013)], but it may not be an accurate measurement of the real costs that farmers incur and, so, is potentially mismeasured. If the measurement error is classical, it may induce an attenuation bias in the OLS estimates.

Second, previously deforested regions may have a higher demand for improvements in local infrastructure conditions, including more and better roads, which leads to reverse causality in the cross-sectional data. Third, roads may have been built in response to profitable situations. A common example states that unobservable (to the econometrician) soil quality for agriculture in

a given location may have induced both deforestation and the presence of roads to access the location. Both the simultaneity and the omitted variable problems may induce the OLS regression to overstate the impact of transportation costs.

In the present case, however, the omitted variable problem does not necessarily lead to an upward bias. As mentioned in Subsection 2.1, early occupations in the Amazon were based on the extraction of rubber. And regions that are well suited for the rubber trees (Hevea brasiliensis) may or may not be well suited for agriculture. The soil quality in the Amazon actually is poor for agriculture in most regions (see Subsection 4). Because good navigable rivers may have been used and past unofficial roads may have been built to access valuable trees (including the wild rubber trees), but more recent roads (and their recent improvements) may have been directed to agricultural regions, it is not clear ex-ante the direction of the bias of the OLS estimator [Pfaff et al. (2009)].

In this paper, I use straight-line distances to the nearest port and to the nearest state capital as instruments for transportation costs. In the following paragraphs I discuss (i) why one should expect straight-line distances to be strong instruments, and (ii) under what conditions one should expect the instruments to satisfy an exclusion restriction condition.

First, it is evident that distances to the nearest port should correlate with the costs to the ports. Furthermore, to the extent that state capitals are connected with better transportation infrastructure, a location close to a state capital should have smaller costs (*ceteris paribus*) to reach the ports. Therefore, the distance to the nearest capital should also be positively correlated with transportation costs.

The conditions under which the instruments satisfy the exclusion restriction are more involved. I start following the discussion presented by Chomitz and Gray (1996). Because locations of major towns - in the present case, ports and state capitals - were determined by geography and historical reasons long before the expansion of the roads in the 1970s, I can construct an exogenous network of roads by linking the major centers with straight-lines.[18] The distances computed using the virtual network should be correlated with transportation costs to ports, because the location of the towns creates links between the major centers, but not the precise routing. Similar to the ports and to the state capitals, most of the municipal seats in the Amazon were established long before the occupation of the Amazon. They were established by late 1800s and early 1900s and, as discussed earlier, not necessarily located in areas where agricultural activity was more valuable. It

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[18] All state capitals and ports used in this paper were established before or during the 19th century, except for Porto Velho (founded in 1907).

is conceivable therefore that the virtual road network is exogenous to the agricultural activities that took place in the Amazon after the 1970s. By noting that using the virtual network and computing straight-line distances directly to the main destinations provide the same information, I opted for the simpler solution.[19]

Although the virtual road network can be viewed as exogenous to the recent agricultural activities, it is still possible that the straight-line distances correlate with factors that affect farmers' decisions to deforest. It is therefore necessary to control for these factors. As discussed in Subsection 3.1, farmers' decisions depend on productivity factors and on farmgate output and input prices. Once these factors are taken into account, straight-line distances do not influence their choices. I therefore control for differences in productivity using measurements of soil quality and various agroclimatic variables. Variation in local prices is explained by variation in transportation costs to the nearest port, at least for tradable goods.

The instruments may be invalid if there are outputs or inputs whose prices are not fixed in the international market. In this case, local market conditions may affect local prices and correlate with straight-line distances to the main destinations. An important example is local labor markets. For instance, wages may have to increase as the municipalities locate further away from the nearest capital, all else being constant, to compensate workers for working away from desired places. Municipalities further away from the capital may deforest less than a location close to the capital because of wage differences. If the wage differences are not controlled for in the regression and correlate with the instruments, then the instruments are invalid. A similar problem may occur if there are other non-tradable inputs and outputs.

To minimize this problem I include in the regressions factors that shift local demand and supply for non-tradable outputs and inputs that may correlate with straight-line distances. I included the local population, the presence of power plants (mainly hydroelectric facilities) and local mining. While the local population shifts the supply of labor and increases the demand for non-tradables, power plants and mining shift both the demand for labor and non-tradables. Although one may be concerned with the endogeneity of population, I included and excluded population in the regressions

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[19]The strategy here is similar to the approach adopted by Banerjee, Duflo and Qian (2012), who studied the impact of transportation costs on local GDP in China. However, differently from their strategy, I do not construct treatment and control groups based on how close a region is to the straight-lines. The differences in deforestation in these regions would not capture the *overall* impacts of roads. It could only explain the *differential* impacts on the groups, which are not sufficient for my purpose. In addition, their strategy does not take into account improvements in roads elsewhere in the transportation network. It cannot therefore capture impacts of improvements to one segment of road that may affect municipalities far away from that segment. I instead consider roads as a network and estimate aggregate impacts of transportation networks in a similar spirit as in Donaldson and Hornbeck (2013).

and the results do not change significantly. I present the estimates in the Supplemental Material.[20]

There are two other factors that may affect farmers' decisions to deforest: the level of enforcement and the potential lack of property rights. In principle both factors could be correlated with straight-line distances. If the difficulty to monitor and punish farms for illegal deforestation is higher for farms located in more pristine areas, then the further away the farm is, the less monitoring there will be, and, so, the more incentives the farmer will have to deforest. In short, the larger the distance, the larger the deforested area. In this case, instrumental variables *underestimate* the impacts of transportation costs. The bias implies that taxes should have larger effects on farmers' willingness to deforest than the estimated here. To investigate this possibility I include the distance to the closest IBAMA agency (the Brazilian Environmental Protection Agency) in the regressions as a proxy for the difficulties in monitoring. The inclusion however does not change the results significantly (see Supplemental Material), which reinforces the interpretation that the legislation has not been enforced.

Another problem is the potential lack of property rights. Historically, farmers had incentives to deforest as a way to secure their land tenure [Andersen et al. (2002)]. It is conceivable then that the farther away the farm is from a state capital, the less secure their land rights are, and, so, the more incentives farmers have to deforest. Similarly to the monitoring efforts problem, the larger the distance, the larger the deforested area. Again, instrumental variables should underestimate the impacts of transportation costs, and taxes should have larger effects than the estimated here. To address this issue I include a proxy for property rights in the regressions. In the Brazilian Agricultural Census, the best proxy for property rights is the proportion of private land with land title. Presumably, the smaller the proportion of land with land titles, the smaller the tenure security. The inclusion of such a proxy however is not without problems. The proxy may be endogenous, as more deforestation may have led to higher proportion of land titles. The proxy may therefore suffer from simultaneity bias. It is not clear ex-ante if this bias would induce an upward or a downward bias in the coefficient for transportation costs. The solution to this problem of course is to use instruments for the proportion of land titles. But finding sources of exogenous variation for property rights within a country is an extremely difficult task - I have no clear instruments in the data set. In sum, the problem here is that excluding a proxy for property rights may underestimate impacts of transportation costs on deforestation, but including it may also cause a bias from the

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[20]Labor is a scarce factor in the Amazon and both medium and large farms are likely land- and capital-intensive, but not labor-intensive. So, the share of wages on costs is probably small. It may be difficult therefore to capture impacts of factors that shift the local demand and supply of labor on deforestation.

simultaneity problem. In spite of all these difficulties, the inclusion and exclusion of the proxy for property rights in the regressions do not affect the estimates significantly (see Supplemental Material). Although both estimates could be equally biased, the results are reassuring. Most farmers do have their land titles (85 percent) and it is possible that they may not need to deforest as much to guarantee their property rights. Or, at least, their land tenure status may not affect how their deforestation decisions relate to transportation costs. In any event, if the estimates are biased, one should expect taxes to have larger effects than the estimated here.[21]

4 Data

Next, I describe the data set. First, I discuss the dependent variable and the endogenous regressor. Then, I present some summary statistics. The set of covariates that I use is: *Soil quality, Temperature, Precipitation, Altitude, Local Population, Local Mining and Local Power Plants.* In the robustness analysis I also use the *Distance to IBAMA* and the *Proportion of Private Land with Land Title.* A detailed description of the variables and the productivity indices is provided in the Supplemental Material.[22]

4.1 Dependent Variable: Deforestation

The land-use classification in the Brazilian Agricultural Census of 2006 is divided into several categories which were aggregated in two: agricultural and forested land. Agricultural land includes pasture and crops, while forested land aggregates managed forests and forests that are not currently being exploited. The groups of farm sizes considered here are: (i) small farms (those with less than 5 hectares); (ii) small-to-medium farms (those with an area between 5 and 50 hectares); (iii) medium-to-large farms (those with an area between 50 and 500 hectares); and (iv) large farms (those with more than 500 hectares).[23]

4.2 Endogenous Regressor: Transportation Costs

The proxy for transportation costs is defined as the minimum unit cost (US\$/ton) to transport one ton of goods to the nearest port. When directed to international markets, the main products

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[21] In case the instruments are invalid even after controlling for all these factors, point identification is lost, but partial identification is still possible. The monotone instrumental variable approach of Manski and Pepper (2000) can be used to partially identify the parameters of interest. I leave this extension for future work.

[22] I am grateful to Professor Eustáquio Reis, who kindly made the soil quality data available; and to Professor Newton de Castro, who suggested the method to compute the transportation costs.

[23] Satellite data would be another option to measure the land use, but it cannot distinguish between deforestation on private and public land. Because the distinction is important here, I opted for the census data.

in the Amazon normally use either the ports in the North (Port of Santana, Port of Belém and Port of Itaqui) or the ports in the South (Port of Santos and Port of Paranaguá), see Figure 1 in Subsection 2.3. I therefore selected these five ports to be the main destinations for the proxy for the transportation costs. The least cost path to the nearest port is computed in ArcGIS using the transportation network for 2006 and the freight rate data collected by SIFRECA (Sistema de Informações de Fretes). Because almost all the information I obtained from SIFRECA for the Amazon corresponded to costs of transporting soybeans, the proxy TC_m measures the minimum cost to transport one ton of soybeans.

4.3   Summary Statistics

There are 528 municipalities in the data set. All municipalities with a positive fraction of their area in the Amazon Biome were included in the sample. Table 1 presents some summary statistics. Farms occupy, on average, about 39 percent of the municipal area; and the fraction of private land used for agriculture is 65 percent on average. The cost to transport one ton of soybean from the South Amazon (the region where the soybean is produced) to the Port of Santos was 30 per cent the price of the soybean at the port - a significant cost for farmers.[24]

Statistics	Mean	Std Dev	Min	Max
Number of Farms	1222	1165	37	11544
Prop. of Farm Area on Municipality Area	0.39	0.27	0	0.98
Prop. of Deforestation on Private Area	0.65	0.2	0.12	1
Cost to Port (US$/ton)	41.5	33.5	0	163
Distance to Port (km)	868	717	0	2627
Distance to Capital (km)	316	219	0	900
Temperature (^{o}C)	26.5	0.56	25	27.5
Rain (mm/year)	184	32	111	272
Altitude (meters)	116	126	0	920
Prop. of Good Soil	0.05	0.17	0	0.99
Prop. of Good/Medium Quality Soil	0.08	0.22	0	1
Prop. of Medium Quality Soil	0.04	0.18	0	0.99
Prop. of Low Quality Soil	0.51	0.38	0	1
Prop. of Unsuitable Soil	0.31	0.35	0	1
Number of Local Mining	0.81	2	0	22
Number of Local Power Plants	0.04	0.2	0	1
Local Population (thousands)	27	147	0.09	2617
Prop. of Land with Land Title	0.93	0.12	0.007	1

Table 1: Summary Statistics

[24]The FOB price of soybean in the Port of Santos in 2006 was approximately US$ 230/ton.

Table 2 provides information about the different farm sizes. The numbers in the cells are sample averages across municipalities. The concentration of land is clear in the table. Despite the fact that large farms are a small proportion of the total number of farms (5 percent), they occupy about 50 percent of the private farmland; while small farms account for 21 percent of the farms and occupy only 1 percent of the private land. The small landholders tend to deforest a large part of their land (90 percent), but the proportion of deforestation diminishes as farm size increases. Remember that the existing legislation requires the deforestation to be less than 20 percent of the properties.[25]

Statistics	Small	Small-Medium	Medium-Large	Large
Number of Farms	302	413	353	46
Prop. of the Number of Farms	0.21	0.33	0.31	0.05
Prop. of the Private Area	0.01	0.11	0.38	0.5
Prop. of Def. on Private Area	0.90	0.71	0.69	0.62
Yields - Crops/Pasture (q^{cp})	0.70	0.41	0.41	0.27
Yields - Crops (q^c)	1.03	1.04	1.16	0.86

Table 2: Summary Statistics by Farm Sizes (Sample Averages)

5 Effects of Transportation Cost on Deforestation

This section presents the estimated impact of transportation costs on deforestation. It begins by reporting the first stage regression to check for the presence of weak instruments, and then it presents the land-use regressions. I leave for the Supplemental Material the results of the SPQIV model because there are no significant differences between the logit and the semiparametric models. This fact suggests that the quantile logit model is sufficiently flexible for the present data set.

5.1 First Stage Regression

Table 3 exposes the results of regressing transportation costs to the nearest port on straight-line distances. For brevity, I omitted the estimated coefficients of the other covariates. It is clear that both straight-line distances to ports and to the nearest capital are strong predictors of costs to ports and that there is no problem with weak instruments in this data set.

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[25] Although not presented in the table, small farms tend to produce perennial crops, mainly manioc, and are primarily located in the Western Amazon. Small-medium and medium-large farms have higher fractions of their land in corn, rice and beans and large farms produce more corn and soybeans. Also, the larger the farm size, the larger the proportion used for pasture. Large farms are primarily located in the South Amazon, while medium sized farms are more frequently located in the East Amazon and in the central regions.

	Costs to Port
Distance to Port	0.087*
	(31.35)
Distance to Capital	0.027*
	(5.67)
Observations	528
F-statistic	487.4
R^2	0.91

t statistics in parenthesis, * p $<$ 0.001.

Table 3: First Stage Regression

5.2 Land-Use Regressions

Next, I present results for the logit models. Table 4 reports the coefficients for costs to the nearest port and the associated t-statistics in parenthesis for the OLS, the 2SLS, the quantile regression (QR), and the instrumental variable quantile regression (IVQR) for each farm size. For brevity, the coefficients of the other regressors are omitted in the table, but they are reported in the Supplemental Material, when I discuss some robustness exercises.[26]

I begin the discussion by comparing the OLS and the 2SLS estimates. Remember that the typical exercise would use OLS to estimate the land-use regressions. As discussed in Subsection 3.3, it is not clear ex-ante what the direction and the magnitude of the bias from OLS estimates should be. The OLS coefficients in Table 4 are small in magnitude and not significantly different from zero. In addition, they predict positive impacts of costs to ports on the share of agricultural land for small and medium sized farms. When transportation costs are instrumented with straight-line distances, the coefficients increase in magnitude (except for smallholders) and their signs become negative for all farm sizes. The results suggest that an attenuation bias from measurement errors in transportation costs may be important in the present data set.

Next I focus on the quantile regressions. The IVQR coefficients for medium sized and large farms are negative, almost all are significant and greater in magnitude than the QR coefficients. The coefficients are not stable across quantiles, so, even after controlling for observable municipality-level variables, farms with different levels of deforested area seem to respond differently to changes in transportation costs.

The heterogeneity in responses across quantiles may be better illustrated graphically. Figure

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[26]The number of municipalities for small farms is 505; for small-medium is 528; for medium-large, 526; and for large farms, 461. For all farm sizes, the overidentification tests fail to reject the null of valid instrumetns. For small farms, the test statistic is 0.15 (p-value=0.7); for small-medium, 1.01 (p-value=0.31); for medium-large 1.45 (p-value=0.22); and for large farms, 0.10 (p-value=0.74).

	OLS	2SLS	Quantiles				
			10	25	50	75	90
Small							
No IV	0.0030	-	0.0038*	0.0025	0.0028	0.0026	0.0105
	(0.94)	-	(2.19)	(1.31)	(1.34)	(0.95)	(1.47)
IV	-	-0.0029	0.0029	0.0018	-0.0002	-0.0013	-0.0027
	-	(-0.84)	(1.66)	(0.89)	(-0.07)	(-0.44)	(-0.16)
Small-Medium							
No IV	0.0001	-	-0.0000	-0.0008	-0.0013	-0.0012	0.0014
	(0.03)	-	(-0.04)	(-0.64)	(-1.02	(-0.69)	(0.49)
IV	-	-0.0034	-0.0005	-0.0017	-0.0034*	-0.0050**	-0.0008
	-	(-1.59)	(-0.42)	(-1.34)	(-2.51)	(-3.36)	(-0.26)
Medium-Large							
No IV	0.0002	-	-0.0048**	-0.0036**	-0.0033*	0.0003	0.0040
	(0.12)	-	(-3.4)	(-2.5)	(-2.15)	(0.21)	(1.59)
IV	-	-0.0041*	-0.0069**	-0.0054**	-0.0051**	-0.0038*	-0.0010
	-	(-2.24)	(-4.75)	(-3.70)	(-3.28)	-2.09)	(0.38)
Large							
No IV	-0.0018	-	-0.0062**	-0.0042**	-0.0051**	-0.0040**	-0.0039
	(-1.01)	-	(-3.96)	(-2.64)	(-3.29)	(-2.09)	(-1.71)
IV	-	-0.0042	-0.0062**	-0.0059**	-0.0063**	-0.0065**	-0.0068*
	-	(1.91)	(-3.51)	(-3.67)	(-4.07)	(-3.59)	(-3.12)

t statistics in parenthesis

* p < 0.05, ** p < 0.01

Table 4: Land-use Regressions by Farm Size - Coefficients for Costs to Ports

3 presents the data and the curves for the quantiles $u = 0.1, 0.2, ..., 0.9$ obtained from the IVQR estimates. The regressors are fixed at the sample average and costs to ports vary over the observed range in the data. It is clear that the small landholders are insensitive to transportation costs - none of their IVQR coefficients are significantly different from zero. This seems reasonable, because small farms tend to be concentrated in isolated regions in the Western Amazon and tend to produce manioc, which is consumed domestically and does not require a significant amount of inputs. They are most likely producing for subsistence and not engaged in the market. Therefore, their decision to deforest must be driven by the shadow value of food, and not by the costs to the nearest port. The model does not seem to be well suited for them and, so, my strategy most likely fails to identify their demand for deforestation. Despite these problems, because smallholders occupy only 1 percent of the private land, their behavior does not play a major role in environmental policies.
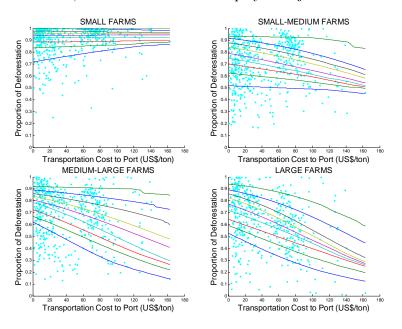

Figure 3: Share of Deforestation vs. Costs to Ports

For other farm sizes, the upper tail quantile curves tend to be concave, while the lower tail quantile curves tend to be convex - which conforms with the discussion in Subsection 3.1.[27]

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[27]To compute the curves in the figure I rearranged the quantiles for each point in the data following the procedure proposed by Chernozhukov et al. (2010) to avoid quantile crossing. The model is estimated for quantiles ranging on $\{0.05, 0.02, ..., 0.95\}$, to avoid problems with extreme quatiles.

6   Demand for Deforestation

This section presents the main results of the paper. First, I show the estimated demand for deforestation on private properties and I discuss how sensible the demand function is to the choice of the productivity index. Second, I present the geographic distribution of land-use under taxes. After the geographic distribution, I discuss the implications for carbon emissions and for the optimal tax. I then discuss the resulting costs for the three policy interventions (taxes, payments and the 80 percent rule), and I close the section with some notes about the limitations of the study.

Figure 4 presents the demand for deforestation for each farm size and the total demand function based on the "fixed-proportions" model. To compute the demand function, I use the IVQR estimates of the logit model together with equation (5) in Section 3.2 to predict the fraction of agricultural land on private properties for each farm size and for each municipality in the dataset. Then, for each hypothetical tax, I compute the total deforested area from the predicted share of agricultural land. By summing over the municipalities, I obtain the corresponding demand for each farm size. Finally, the total demand is obtained by summing over the farm sizes. An implicit assumption in this calculation is that taxes would not change the distribution of the farm sizes. Altought taxes could affect the sizes of the farms, such impacts are out of the scope of this paper. See a brief discussion of this point in Subsection 6.4.
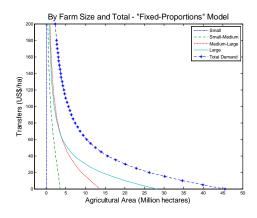

Figure 4: Demand for Deforestation

One may interpret the total demand in figure 4 in the following way: if the government had increased the relative value of the forested land by imposing a perfectly enforced tax charging, say, US$ 40/ha of agricultural land per year, farmers would be willing to use approximately 15.6 million hectares for agriculture (20 percent of the private properties) instead of the actual 46.2 million hectares (60 percent). Because farmers' average gross revenue per hectare in the Amazon in 2006

was US$ 120/ha, such a tax would drive many farmers out of production.[28]

It is clear from figure 4 that the shape of the total demand mainly comes from the demand of large farms. Policies targeting small landholders are therefore unlikely to promote significant conservation.

Figure 5 compares the demand for deforestation based on the "fixed-proportions" model and the demand based on the "vertical" model. As discussed in Subsection 3.2, the demand based on the "vertical" model is above the curve based on the "fixed-proportions" model, implying smaller impacts from taxes. One may view the "vertical" demand curve as an upper-bound for any demand curve with flexible substitution patterns among the different agricultural land-uses.
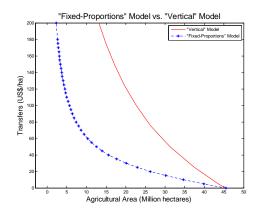

Figure 5: Demand for Deforestation - Different Specifications

6.1 Geographic Distribution

In Figure 6, I present the geographic distribution of the demand function based on the "fixed-proportions" model. The left panel presents the total agricultural area computed from the Census data. The darker the region, the larger the agricultural land. The middle panel presents the counterfactual agricultural land for taxes of US$ 40/ha; and the right panel, the corresponding map for taxes of US$ 100/ha.[29]

Farmers in the "Arc of Deforestation" would respond less to taxes. Even under a tax of US$ 100/ha, farmers in the South Amazon, the region where the soybean is produced, would be willing to use their land intensively. The opportunity costs of the agricultural area in this region is probably too high to not be used for agriculture. Forests in central and western regions could have been

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[28]Instead of a perfectly enforced tax of US$ 40/ha, one may interpret the results in terms of expected taxes that farmers pay.

[29]The numbers in the legend correspond to the quantiles of the agricultural area in the data. The quantiles are $\{0.01, 0.05, 0.1, 0.2, 0.3, ..., 0.9\}$.
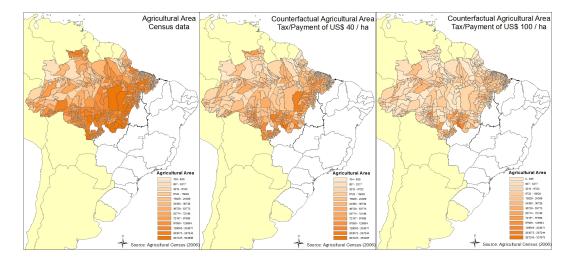
Figure 6: Geographic Distribution of the Demand for Deforestation

more preserved and so less fragmented, which might be beneficial from a biodiversity point of view.

6.2 Emissions of CO_2 and Optimal Tax

Avoided Emissions Implications for emissions of carbon require estimates of the carbon stock in forested and deforested areas. Baccini et al. (2012) recently measured the geographic distribution of the aboveground carbon stock in Brazil. I combined their map of carbon stock with the maps of deforestation from satellite images [INPE (2010)] and computed for each municipality the difference of carbon stock in forested and deforested areas. Different municipalities may have different carbon stock in forests and in agricultural areas because forests are heterogeneous and the alternative land-uses in agriculture may conserve more or less carbon on the ground. The average difference is 78 tons of carbon per hectare (tC/ha).

Combining the differences in carbon stocks with the demand for deforestation resulted in a "supply of avoided emissions." Figure 7 presents this supply function. One may interpret the curve in the following way: if a carbon tax of (or a REDD+ program paying) US\$ 1 per ton of CO_2 per year were implemented, farmers would be willing to deforest less and, as a result, would avoid the emissions of approximately 4 billion tons of carbon. The avoided emissions correspond to approximately 4.4 years of worldwide emissions from land-use change during 2002 to 2011 [IPCC (2013)]. The elastic part of the curve is the result of the large stocks of carbon in forested areas and the fact that farmers would be responsive to taxes. The vertical part is the result of capacity constraint: with higher taxes, farmers would be willing to keep most of the total private land forested.[30]

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[30]The calculation assumes that (i) the difference of the carbon stock in forested and deforested areas would be
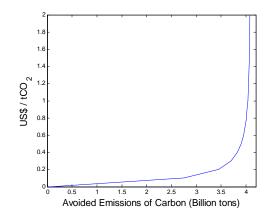
27

Figure 7: Avoided Emissions of CO2

A carbon tax of US$ $1/tCO_2$/year is significantly smaller than the average price of carbon in the European Union Emissions Trading System. For example, by the end of 2012 the price was US$ $8.75/tCO_2$. The difference in prices suggests substantial opportunities for trade, but such opportunities have not yet taken place. A possible reason lies on potentially large transaction costs. Measuring and monitoring the amount of carbon stocks may be expensive. Perhaps more important, measuring avoided emissions depends on the counterfactual emissions that would occur in the absence of payments - which is not trivial to compute.

Optimal Tax   The value of an optimal Pigouvian tax is the marginal damage of the externalities caused by deforestation, such as emissions of carbon and biodiversity loss. Because it is difficult to measure the production of all the externalities and to value the corresponding damages, a lower bound on the optimal tax can be obtained from the estimated damages associated with an incremental change in CO_2 emissions. According to Greenstone et al. (2011), the central value of the social cost of carbon for 2010 was US$ $21/tCO_2$ (2007$). As figure 7 shows, imposing this tax would virtually eliminate the agricultural land in the Amazon.[31]

The Amazon is responsible for 20 percent of the Brazilian agricultural area. If no land in the Amazon were used for agriculture, one should expect non-trivial impacts on the local economy, on Brazil's trade balance, and possibly on international prices of beef and soybeans. Increases in the prices of these products could diminish the welfare from consumption of food. In addition, more

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released into the atmosphere once the forest is clear-cut for agriculture. It therefore ignores the decay rate. It also assumes that (ii) the carbon taxes would not affect the amount of carbon stock in agricultural land. But, in principle, farmers could respond to carbon taxes by using new techniques that conserve the carbon on the ground. One ton of carbon corresponds to $(44/12)$ tons of CO_2. The shape of the supply function is similar to other studies; see, e.g., Nepstad et al. (2007).

[31] The calculation converts dollars from 2007 to 2006 using US Consumer Price Index data (CPI).

deforestation in other locations could occur, a problem known as "leakage". The present paper does not take these effects into account.

6.3   The Costs of the Policy Interventions

Brazil adopted a "command-and-control" policy instrument that obligates farmers in the Amazon to keep 80 percent of their land in native forest. I calculated a lower bound for the hidden cost of this policy by means of a perfectly enforced Pigouvian tax that induces farmers to only use 20 percent of their properties for agriculture. I computed this tax for each municipality and for each farm size using the "fixed-proportions" model. The corresponding farmers' lost surplus from the taxes is the sum of the trapezoid areas below each demand curve. The sum resulted in US$ 4.7 billion. Farmers may therefore be willing to pay US$ 4.7 billion per year to avoid the enforcement of this rule. Not surprisingly, farmers have systematically tried to alter the legislation since its implementation [Alston and Miller (2008)].[32]

A uniform tax charging US$ 40/ha/year of agricultural land also would induce 20 percent of agricultural land, but it would have been roughly ten times cheaper: farmers' lost surplus would have been approximately US$ 484 million per year - provided the tax revenues were redistributed to them. And tax revenues would have been approximately US$ 627 million per year (0.35 percent of the Brazilian federal budget for 2006). The 80 percent rule is not a cost-effective policy: the more productive farms would have to use less land for agriculture and, so, would have forgone more profits when compared to taxes.[33]

The geographic distribution of the demand for deforestation is relevant when computing the costs of the 80 percent rule. Each municipality may need different levels of local taxes for different farm sizes to induce farmers to use only 20 percent of their land. The differences may have non-trivial impacts on aggregate results. Note from Table 4 that medium sized farms located in places with high levels of unobservables (quantiles) respond less to transportation costs. They therefore have more inelastic demand for deforestation when compared to other quantiles. It would be necessary to impose higher local taxes to induce them to use 20 percent of agricultural land. The

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[32]In actuality, the amount of money they might be willing to pay must be even larger for three reasons: (i) the "command-and-control" policy imposes the same limit on farmers' land-use regardless of the differences in opportunity costs of agricultural land, while I make use of local Pigouvian taxes, which is a cost-effective price instrument; (ii) the legislation does not allow for managed forests in preservation areas, except under very stringent conditions, but the forested area in the data includes managed forests; and (iii) now that the land is opened, the costs to replant the vegetation adds to the farmers' total costs, since, by law, they must recover the forest at their own expense.

[33]Note that the fines specified in the legislation, ranging from US$ 2,300/ha to US$ 23,000/ha, could be more than sufficient to induce less than 20 percent share of agricultural land if they were perfectly enforced. Such high values for the fines however do not seem necessary. The Brazilian government could be more effective in protecting the rainforest by reducing the value of these fines and increasing enforcement simultaneously.

combination of inelastic demand and high local taxes increase their lost surplus. Depending on the importance of these groups and on the amount of their losts surpluses, their impacts on the total costs of the 80 percent rule may be substantial. The 2SLS estimator, however, cannot capture such differences as it ignores the distribution of impacts. It therefore estimates different local demands for deforestation, with different local taxes and, so, different total costs. The total lost surplus of the 80 percent rule from the 2SLS estimator is US\$ 3.25 billion. The smaller lost surplus from the 2SLS estimator compared to the IVQR estimator points to the importance of the heterogeneity in the demand for deforestation in computing the aggregated costs of policies.

Finally, to provide a complete picture of the policies, payments of US\$ 40/ha also would result in 80 percent of forest cover, but the total cost would have been US\$ 2.5 billion per year (1.4 percent of the Brazilian federal budget for 2006), not included transaction and monitoring costs. And a perfectly targeted policy paying farmers who were going to deforest, but *not* paying those who were *not* going to deforest would reduce the non-targeted costs by a half (US\$ 1.2 billion per year). Perfect targeting, however, is unlikely because of asymmetric information problems [Ferraro (2008)].

6.4 Limitations

The paper has some limitations that I briefly discuss next. First, the economics costs of the policies do not take into account monitoring and transaction costs. Second, there is no equilibrium analysis considered here - only farmers willingness to deforest. Third, and similar to the previous point, I have not estimated by how much the total private land (and the land distribution) would respond to the policies. Although such an exercise is possible, there are some important implications that cannot be addressed with the present data set. There exists plenty of unprotected public forested land that may be occupied in response to payment programs, for example. The occupations might reduce the potential effectiveness of the programs, increase their total costs, and increase disputes for land and the potential violence associated with these disputes. As such, payment programs, if not carefully designed, may have the unintended consequences of raising local violence. The results I present should be viewed therefore as only one of the many inputs necessary for a complete evaluation of the preservation policies in the Amazon.

7   Conclusion

I estimated farmers' demand for deforestation on private properties in the Brazilian Amazon. The main policy implications of this exercise are the following: (i) Pigouvian taxes could have been effective in avoiding deforestation and emissions of carbon; (ii) the taxes should *not* target small landholders; and (iii) the existing legislation would have been expensive for local farmers when compared to other policies.

There are several directions for future research. First, accessing the micro-data on farmers' decisions may provide a richer picture of their opportunity costs and avoid the potential drawbacks in using aggregated measures for the local yields. Furthermore, it may reveal the entire distribution of farmer's private valuations within each municipality, which may help address issues such as the use of auctions to allocate PES contracts.

Second, a panel data based on satellite images - coupled with extra assumptions on the evolution of the private land - allows for a dynamic model with irreversible land-use decisions. It can be used to study impacts of commodity prices on the rate of deforestation and by how much these prices can affect the effectiveness of the policy interventions. Third, the framework presented here can be used to study impacts of improvements of roads on deforestation. This is an important topic because the Brazilian government is paving some unpaved roads in the Amazon to reduce the costs of exporting commodities.

References

[1] Alix-Garcia, J., E. Shapiro, and K. Sims. (2012). "Forest Conservation and Slippage: Evidence from Mexico's National Payments for Ecosystem Services Program," *Land Economics*, 88(4):613-638.

[2] Andersen, L.E., C. W. Granger, E. Reis, D. Weinhold and S. Wunder. (2002). *The Dynamics of Deforestation and Economic Growth in the Brazilian Amazon*, Cambridge Univ. Press.

[3] Andersen, L. E. and E. J. Reis (1997) "Deforestation, Development, and Government Policy in the Brazilian Amazon: An Econometric Analysis." In: Hickey, Kevin L. & Demitri Kantarelis (1997) *Our Natural Environment: At a Crossroad*. Worchester, MA: Interdisciplinary Environmental Association.

[4] Assuncao, J., C. Gandour and R. Rocha (2012) "Deforestation slowdown in the legal Amazon: Prices or Policies?," Climate Policy Initiative Working Paper.

[5] Aston, L. J. and B. Muller (2008). "Legal Reserve Requirements in Brazilian Forests: Path Dependent Evolution of De Facto Legislation." *Revista EconomiA*, Selecta, Brasília (DF), v.8, n.4, 25-53.

[6] Baccinni

[7] Banerjee, Duflo and Qian (2009), "On the Road: Access to Transportation Infrastructure and Economic Growth in China," Mimeo.

[8] Berry, S. T.

[9] Berry, S. T. and P. A. Haile (2011). "Identification in Differentiated Products Markets Using Market Level Data," Discussion paper, Yale University.

[10] Brito, B. and P. Barreto (2006). "Sugestões para Aumentar a Eficácia da Lei de Crimes Ambientais no Ibama e nos Tribunais de Justiça no Setor Florestal do Pará". 11° Congresso Brasileiro de Direito Ambiental: Biodiversidade e Direito em São Paulo. São Paulo.

[11] Börner, J., S. Wunder, S. Wertz-Kanounnikoff, M. R. Tito, L. Pereira and N. Nascimento (2010). "Direct Conservation Payments in the Brazilian Amazon: Scope and Equity Implications," *Ecological Economics*, 69, 1272–1282.

[12] Castro, N. (2003). "Formação de Preços no Transporte de Carga," *Pesquisa e Planejamento Econômico*, v.33, n.1, 167-189.

[13] Chen, X. and D. Pouzo (2011). "Estimation of Nonparametric Conditional Moment Models With Possibly Nonsmooth Generalized Residuals," forthcoming in *Econometrica*.

[14] Chernozhukov,V. and C. Hansen (2008). "Instrumental Variable Quantile Regression: A Robust Inference Approach," *Journal of Econometrics*, Volume 142, Issue 1, 379-398.

[15] Chernozhukov, V., I. Fernández-Val and A. Galichon (2010). "Quantile and Probability Curves Without Crossing," *Econometrica*, 78, Issue 3, 1093-1125.

[16] Chomitz, K. M. and D. A. Gray (1996). "Roads, Land Use and Deforestation: A Spatial Model Applied to Belize". *World Bank Economic Review,* 10(3):487-512.

[17] Donaldson and Hornbeck

[18] Foster and Rosenzweig

[19] Greenstone, M., E. Kopits, and A. Wolverton (2011). "Estimating the Social Cost of Carbon for Use in U.S. Federal Rulemakings: A Summary and Interpretation," NBER Working Paper Series, w16913.

[20] Hirakuri, S. R. (2003). *Can Law Save the Forest? Lessons from Finland and Brazil.* Jacarta, Indonesia, Centre for International Forestry Research.

[21] Houghton, R.A., Lawrence KT., Hackler J.L., Brown S. (2001). "The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates," *Global Change Biology*, 7:731–746.

[22] Manski, C. F. and J. V. Pepper (2000). "Monotone Instrumental Variables: With an Application to the Returns to Schooling," *Econometrica*, 68, Issue 4,997-1010.

[23] Nelson, G.C., Geoghegan, J., (2002). "Modeling deforestation and land use change: sparse data environments." *Agricultural Economics* 27.

[24] Nepstad, D., G. Carvalho, A. C. Barros, A. Alencar, J. P. Capobianco, J. Bishop, P. Moutinho, P. Lefebvre and U. Silva Jr. (2001). "Road Paving, Fire Regime Feedbacks, and the Future of Amazon Forests." *Forest Ecology & Management*, 154. 395-407.

[25] Nepstad et al (2007) REDD+

[26] INPE, Instituto Nacional de Pesquisas Espaciais (2010), *Monitoramento da Floresta Amazônica Brasileira por Satélite – Projeto Prodes.* Available at: <http://www.obt.inpe.br/prodes/>

[27] IPCC (2007). *Climate Change 2007: The Physical Science Basis.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[28] IPCC (2013). *Climate Change 2013: The Physical Science Basis.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[29] Pereira, D., D. Santos, M. Vedoveto, J. Guimarães and A. Veríssimo (2010). *Fatos Florestais da Amazônia 2010.* Belém, PA: Imazon.

[30] Pfaff, A. (1999). "What Drives Deforestation in the Brazilian Amazon? Evidence from Satellite and Socioeconomic Data". *Journal of Environmental Economics and Management.* 37, 26.

[31] Pfaff et al (2009)

[32] PNLT, National Highway Plan (2006). Available at

http://www.transportes.gov.br/index/conteudo/id/36604 and accessed on 11/24/2010.

[33] Reis, E.J. and R. Guzman (1992). "An Econometric Model of Amazon Deforestation," IPEA, Rio de Janeiro, Brazil.

[34] Saatchia,S.S., N. L. Harrisc, S. Brownc, M. Lefskyd, E. T. A. Mitcharde, W. Salasf, B. Zuttaa, W. Buermannb, S. L. Lewisg, S. Hagenf, S. Petrovac, L. Whiteh, M. Silmani, and A. Morelj (2011). "Benchmark Map of Forest Carbon Stocks in Tropical Regions Across Three Continents," *PNAS*, vol. 108, no. 24, 9899–9904.

[35] Scott, P. T. (2013) "Dynamic Discrete Choice Estimation of Agricultural Land Use," Tolouse School of Economics

[36] Souza-Rodrigues, E. A. (2012). "Supplement to 'Demand for Deforestation in the Amazon'" Available at: https://sites.google.com/site/eduardorodriguesyale2012/research

[37] TCU, Tribunal de Contas da União (2009). "Arrecadação de multas administrativas - Exercício de 2009". Available at: http://portal2.tcu.gov.br/portal/page/portal/TCU/comunidades/contas/

[38] Timmins

[39] Weinhold, D. and E.J. Reis (2008). "Transportation costs and the spatial distribution of land use in the Brazilian Amazon". *Global Environmental Change* 18:54-68.

[40] Wunder, S. (2007). "The Efficiency of Payments for Environmental Services in Tropical Conservation." *Conservation Biology* 21(1): 48–58.