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Technical Paper

Deforestation Slowdown in the Brazilian Amazon: Prices or Policies?

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Abstract

This paper investigates the contribution of agricultural output prices and policies to the 2000s reduction in Amazon deforestation. Based on a panel of Amazon municipalities from 2002 through 2009, we first show that deforestation responded to agricultural output prices. After controlling for price effects, we find that conservation policies implemented beginning in 2004 and 2008 significantly contributed to the curbing of deforestation. Counterfactual simulations suggest that conservation policies avoided approximately 73,000 square kilometers of deforestation, or 56% of total forest clearings that would have occurred from 2005 through 2009 had the policies adopted beginning in 2004 and 2008 not been introduced. This is equivalent to an avoided loss of 2.7 billion tonnes of stored carbon dioxide.

Keywords: deforestation, conservation policies, agricultural prices, Amazon
JEL codes: Q23, Q12

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1. Introduction

Deforestation and biomass decay, in large part originating from the clearing of tropical forests, have contributed almost a fifth of global greenhouse gas emissions (IPCC, 2007). In light of this, the extent of forest clearings in the Brazilian Amazon, the planet's largest rainforest tract and an important carbon sink, raises significant concerns. With currently over 3.2 million square kilometers of remaining native vegetation, the region has long been the world's most active agricultural frontier in terms of forest loss and CO_2 emissions (FAO, 2006). In Brazil, the conversion of forest area and land use change has accounted for over 75% of the country's total net CO_2 emissions (Ministério de Ciência e Tecnologia, 2010).

Yet, the pace of forest clearings in the Brazilian Amazon slowed down substantially in the second half of the 2000s. After peaking at more than 27,000 square kilometers per year in 2004, the Amazon deforestation rate fell sharply over the following years to about 7,000 square kilometers in 2009 (INPE, 2012). Understanding how to best combat tropical deforestation — and thereby simultaneously tackle the threats of climate change and irreversible loss of biodiversity — has become a topic of global concern (Burgess et al., 2012). Although crucial from both national and international policy perspectives, empirical knowledge about the drivers of the recent decrease in Amazon deforestation is still scant.

Figure 1 reveals two potential explanations for the deforestation slowdown. On the one hand, the Amazon deforestation rate appears to be highly correlated with agricultural output prices, specially in the first half of the decade. While price increases provide incentives for producers to convert forest areas into farmland to profit from expanded production, price decreases inhibit this behavior and thereby alleviate the pressure on forests. Market conditions — namely falling agricultural commodity prices in the mid-2000s — may thus have contributed to contain forest clearings. On the other hand, Brazilian conservation policies aimed at controlling and preventing deforestation in the Amazon underwent significant revisions during the 2000s, marked by two key policy turning points. First, the launch of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) in 2004 integrated action across different government institutions and introduced novel procedures for monitoring, environmental control, and territorial management. Second, new policy measures implemented beginning in 2008 targeted municipalities with critical rates of deforestation and conditioned rural credit upon proof of borrowers' compliance with environmental regulations. As shown in Figure 1, the policy turning points were followed by sharp drops in deforestation rates, suggesting that conservation policies helped curb deforestation.

[Figure 1 about here.]

In this paper, we asses the contribution of agricultural prices and conservation policies to the recent Amazon deforestation slowdown. The empirical challenge we face is twofold. First, we must disentangle the effect of policies from potentially relevant price effects. Second, we must explore cross-sectional variation in our empirical setting to identify the effect of policies, isolating it from other contemporaneous effects.

As a starting point, we develop a conceptual framework in which, given a set of parameters regarding endowments, prices, and policies, the representative farmer chooses optimal farmland size to maximize profits. There is no heterogeneity across farmers, and the size of aggregate landholdings within the locality is given. The area that is suitable for production within landholdings therefore determines the tightness of the land constraint faced by the farmer. Optimal farmland size increases with agricultural prices and, to expand farmland beyond his endowment of land, a farmer must deforest. In this setting, conservation policies would be binding whenever optimal farmland size is larger than the landholding that is suitable for agricultural production.

This framework yields two main implications that guide our empirical analysis. First, it indicates that we must control for agricultural output prices to evaluate the impact of conservation policies on deforestation. Second, it suggests that the farmer's response to changes in policy stringency depends on the tightness of the land constraint he faces. In particular, conservation policies are expected to have no effect in places where the area that is suitable for production within landholdings is large enough to fully accommodate optimal farmland. We should therefore only expect policies to be effective in places where land constraints for agricultural production are tight. This second implication introduces cross-sectional variation in response to a new policy across localities with different land endowments. Recent work on deforestation policy impacts also exploring this idea have acknowledged the importance of considering location in policy planning to help predict heterogeneous effects of policy on deforestation. As argued, policy impacts vary across locations because baseline deforestation depends on location-specific characteristics, such as market distances and geography (Pfaff and Robalino, 2012).

We use this conceptual framework to guide our empirical evaluation of the effectiveness of conservation policies introduced beginning in 2004 and 2008, as well as of the role played by agricultural output prices in the 2000s Amazon deforestation slowdown. Our analysis is based on a 2002 through 2009 municipality-by-year panel of data containing municipalities from four Legal Amazon states.[2] Our main dependent variable, the normalized annual

[2]The Legal Amazon is a socio-geographic division of Brazil. It is composed of the western territory of the state of Maranhão and the entire territory of the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins.

deforestation increment, is constructed from satellite-based deforestation data.[3]

The sets of conservation policies are represented by two time dummy variables — one for each of the 2004 and 2008 policy turning points — and their interaction with a measure of the tightness of land constraints at the municipality level. Our first coefficient of interest thus captures policy impacts on deforestation by comparing deforestation trends before and after 2004, in municipalities where the tightness of land constraints is lower compared to those where it is higher. Our second coefficient of interest is analogously defined for 2008.[4] Implications from our conceptual framework guide our choice of two alternative proxy variables for the tightness of land constraints. Our baseline proxy is a measure of the share of land that is not legally available to farmers for use in agricultural production relative to total municipal land area, since conservation policies are expected to be more binding in municipalities with tighter land constraints. The deforestation increment recorded in 2004, which refers to the 2003 peak in agricultural commodity prices, serves as an alternative proxy. Our model suggests that observed deforestation behavior can reflect the underlying tightness of land constraints, with periods marked by more intense deforestation indicating binding land constraints. The interaction between the proxy and the policy turning points thus results in policy variables with sharp time and cross-sectional variation within our municipality-level panel of data.

We take advantage of our data set's panel structure to control for municipality fixed effects, year fixed effects, and municipality-specific time trends, thereby filtering out the impact of intrinsically different municipal characteristics, common shocks, initial conditions, and differences in municipality-level dynamics. We argue that, since the tightness of the land constrain is determined by either fixed or slow-moving factors at the municipality level, and conditioned upon high-frequency variation in market forces, the variation captured by our policy variables should be orthogonal to any latent determinant of deforestation in our empirical setting.

We first analyze the effect of crop and cattle prices on deforestation. For crops, we apply principal component analysis to build an annual crop price index that captures most of the joint variation in five crop price series. We use the lagged crop price index to account for the timing of crop farming decisions in the Amazon. For cattle, we consider prices for current and lagged periods to capture the effect of potential cattle ranching cycles. Cross-

[3]From the National Institute for Space Research's (INPE) Project for Monitoring Deforestation in the Legal Amazon (PRODES).

[4]More precisely, given that deforestation in the Brazilian Amazon is measured within a 12-month window starting in August of each year, we are thus comparing deforestation that occurred before and after August 2004 (2008). As detailed in later sections, this matches the timing of the phase-in of changes to environmental regulations starting in the second semester of 2004 (2008).

sectional variation in price indices is obtained using agricultural output prices recorded in a non-Amazon Brazilian state, weighted by the relative importance of each agricultural product at the municipal level. Results indicate that deforestation is sensitive to crop and cattle prices, even after controlling for year and municipality fixed effects, as well as for municipality-specific time trends. Our findings suggest that crop and cattle prices exhibit different dynamic relationships with deforestation.

Having shown that agricultural output prices affect deforestation, we perform policy impact evaluation controlling for prices. Results indicate that the conservation policies associated with the policy turning points were effective at curbing Amazon deforestation. In counterfactual simulations we estimate that, had the set of conservation policies implemented beginning in 2004 and 2008 not been introduced, deforestation in sample municipalities from 2005 through 2009 would have added up to more than 130,000 square kilometers. Yet, observed sample deforestation in this period totaled about 57,000 square kilometers — 56% less than in the absence of the policies. Our results therefore suggest that conservation policies avoided 73,000 square kilometers of Amazon forest clearings.

We take a first step in the direction of cost-benefit analysis by performing a simple calculation of the monetary benefits of protecting the forest. We find that the 73,000 square kilometers of avoided deforestation are equivalent to a store of 2.7 billion tonnes of carbon dioxide.[5] Given the price of 5 USD/tCO_2 commonly used in current applications, this store is valued at USD 13.2 billion.

We also investigate whether the conservation policies associated with the two policy turning points affected key economic variables at the municipality level. Results indicate that policies had no negative impact on population trends and municipal GDP per capita. This is a qualitatively important finding that suggests there is no relevant trade-off between conservation policies and local development in the Amazon. We further examine this topic by focusing on agricultural sector outcomes. Results support the perception that the recent Amazon deforestation slowdown has not been accompanied by any major downturn in the agricultural sector.

Our empirical findings yield important policy implications for the design of payment for environmental services (PES) policies. Given that agricultural commodity prices are shown to be relevant drivers of Amazon deforestation, the shadow price of preserving the forest is expected to change with changing agricultural prices. Output price variations should therefore be incorporated into PES compensation schemes to ensure producers' forest clearing

[5]Estimations are based on a conversion factor of 10,000 tC/km^2 (36,700 tCO_2/km^2), as established in MMA (2011).

incentives do not surpass their preservation ones at any one point in time. To the best of our knowledge, compensation schemes that vary according to agricultural output prices have not been implemented in current PES setups.

The remainder of this paper is organized as follows. Section 2 presents an overview of the related literature. Section 3 provides the policy background for the analysis. Section 4 introduces and develops the conceptual framework. Section 5 describes the data set and the main variables. Section 6 details our empirical strategy. Section 7 discusses the results. Section 8 performs robustness checks. Section 9 concludes.

2. Related Literature

The economic literature on the determinants of tropical deforestation has made significant progress since its mid-1980s origins. Initial efforts to identify the economic causes of tropical deforestation focused mostly on cross-country or selective country-level analyses, while later efforts turned to microeconomic modelling to investigate household and firm level drivers of tropical deforestation (Angelsen and Kaimowitz, 1999; Barbier and Burgess, 2001).

A substantial stream of this literature is dedicated to documenting the impact of long-run economic drivers of deforestation, such as population pressures, income level and economic growth, technological change, soil quality, and climate (Cropper and Griffiths, 1994; Panayotou and Sungsuwan, 1994; Barbier and Burgess, 1996; Chomitz and Gray, 1996; Cropper et al., 1997; Pfaff, 1999; Chomitz and Thomas, 2003; Foster and Rosenzweig, 2003). The influence of factors affecting household and firm-level forest clearing decisions has also received significant attention in the literature. Rising agricultural output prices, rural credit, roads and road building, and tenure insecurity have been identified as some of these more immediate causes of deforestation (Reis and Margulis, 1991; Panayotou and Sungsuwan, 1994; Reis and Guzmán, 1994; Barbier and Burgess, 1996; Chomitz and Gray, 1996; Pfaff, 1999; Pfaff et al., 2007; Araujo et al., 2009; Hargrave and Kis-Katos, 2013).

This paper contributes to the literature on drivers of deforestation in four ways. First, our core analysis evaluates the role of conservation policies as possible deterrents of forest clearing activity. In particular, we evaluate the impact of broad changes in land use regulation on deforestation at the local level. Despite being potentially crucial to shape economic incentives that determine household and firm-level land use decisions, changes in environmental regulation have been relatively less studied in micro-level impact evaluations. Existing studies looking at specific contexts have found that institutional factors and restrictive regulations can help mediate market demand influences on natural resources (e.g. see the case of fishery management studied in Reddy et al. (2013)). However, sources of exogenous within-country variation in policy adoption are often rare, while longitudinal data typically suffer from both quality and time frame limitations. Within this context, many approaches tend to be only descriptive, such as those provided in Ewers et al. (2008) and Mendonça et al. (2012); see Pfaff et al. (2013) for an overview of studies regarding policy impacts on deforestation. Recently, the greater availability of satellite data on land cover has helped promote the evaluation of specific policy interventions, particularly those for which spatial or geographical factors are most relevant. This is the case of protected areas, which have been the focus of many recent attempts to evaluate conservation policy effectiveness (Andam et al., 2008; Pfaff et al., 2009; Sims, 2010; Soares-Filho et al., 2010; Joppa and Pfaff, 2011; Nelson and Chomitz, 2011; Pfaff et al., 2014; Ferraro et al., 2013; Nolte et al., 2013). Burgess et al. (2012) explore another dimension of the impact of institutional change on deforestation, examining how local officials' incentives affect forest clearing activity. In this paper, we exploit key local heterogeneities to gain cross-sectional variation in how binding conservation policy actually was. Similarly to the existing studies, we argue that policy impacts vary across locations because baseline deforestation depends on location-specific characteristics. This strategy allows us to advance with the evaluation of major policy interventions in the Brazilian Amazon, as well as test whether conservation policies played a relevant role in what was one of the greatest declines in deforestation rates recently experienced by a developing country.

Second, our study contributes to the investigation of the causal effects of market forces on forest clearings. The earlier literature provides evidence that higher agricultural output prices stimulate forest clearings (Panayotou and Sungsuwan, 1994; Andersen, 1996; Barbier and Burgess, 1996; Angelsen and Kaimowitz, 1999; Barbier and Burgess, 2001). Yet, more recent studies have found mixed results regarding the significance and even the direction of the correlation between agricultural output prices and Amazon deforestation (Ferraz, 2001; Arima et al., 2007; Barreto et al., 2008; Araujo et al., 2009; Hargrave and Kis-Katos, 2013). The lack of reliable microeconomic data and exogenous variation in agricultural output prices at the local level limits the identification of price effects (Angelsen and Kaimowitz, 1999; Arcand et al., 2008). In this paper, we show that agricultural output prices recorded at a non-Amazon Brazilian state serve as indicators of local market conditions in the Amazon. We then use these non-Amazon prices to explore exogenous variation in constructed agricultural price indices and assess their effect on deforestation.

Third, it investigates the causes of a specific deforestation phenomenon that has seldom been explored in the literature — the recent Amazon deforestation slowdown. Although several studies focus on understanding the determinants of deforestation specifically in the Brazilian Amazon (Reis and Margulis, 1991; Reis and Guzmán, 1994; Pfaff, 1999; Chomitz and Thomas, 2003; Arima et al., 2007; Pfaff et al., 2007; Weinhold and Reis, 2008; Araujo et al., 2009; Hargrave and Kis-Katos, 2013), there is scarce empirical evidence on the immediate drivers of the sharp decrease in Amazon deforestation observed in the second half of the 2000s. In this paper we not only focus on disentangling the effects of policies and market forces on deforestation, but also evaluate the aggregate policy impact on deforestation, and take a first step in the direction of a cost-benefit analysis. To the best of our knowledge, this is the first paper to implement such aggregate analysis, which is useful for policy design.

Finally, our paper also speaks to the literature on the relationship between economic growth and forest preservation. A consensus is yet to be established in the literature, with existing empirical evidence to support both the absence of a significant positive relationship between income and forest growth (Cropper and Griffiths, 1994; Panayotou, 1995), and the possibility of there being a positive relationship for income levels above a certain threshold (Antle and Heidebrink, 1995) or within closed economies (Foster and Rosenzweig, 2003). In this paper, we conduct empirical exercises to investigate how the agricultural sector in Brazil behaved during the Amazon deforestation slowdown. From a general perspective, this directly contributes to the ongoing debate about the relationship between economic growth and the environment (Grossman and Krueger, 1995; Arrow et al., 1996).

3. Institutional Context

Throughout the 2000s, the Brazilian federal government and the Ministry of the Environment (MMA) sought to inhibit forest clearings and promote forest conservation by focusing on three main policy efforts: strengthening monitoring and law enforcement; expanding protected territory; and adopting a conditional rural credit policy. The pursuit of these efforts led to intense reformulation of conservation policies throughout the decade, with two years standing out as important policy turning points: 2004 and 2008.

3.1. 2004: A New Action Plan

The launch of a novel action plan for combating deforestation in 2004, the PPCDAm, marks the first policy turning point. The plan's foundations date back to July 2003, when the heads of thirteen key Ministries were brought together under the direction of the Chief of Staff to propose and coordinate actions aimed at reducing deforestation in the Legal Amazon.[6] In March 2004, the group presented the operational project for the PPCDAm, a large set of strategic conservation measures to be implemented and executed as part of a

[6] The Chief of Staff of the Presidency of the Republic is the highest-ranking member of the Brazilian Executive Office.

collaborative effort between federal, state, and municipal governments, alongside specialized organizations and civil society. The project focused on three main areas: (i) territorial management and land use; (ii) command and control; and (iii) promotion of sustainable practices (Casa Civil, 2004).

The PPCDAm introduced a new form of dealing with deforestation in the Brazilian Amazon. Conservation efforts were henceforth based on integrated action and participation of the highest levels of the federal government — never before had numerous ministries been simultaneously involved with combating deforestation (IPAM, 2009; Maia et al., 2011). Moreover, the mobilization of key organizations - particularly the National Institute for Space Research (INPE), the Federal Police, the Federal Highway Police, and the Brazilian Army - and the contribution of the Chief of Staff as orchestrator of joint action enabled the implementation of innovative procedures for monitoring, environmental control, and territorial management (IPAM, 2009).

Several of the changes to Brazilian forestry and conservation policy that were introduced in the second half of the 2000s happened within the PPCDAm framework. Remote sensing-based Amazon monitoring capacity improved significantly with the creation of the Real-Time System for Detection of Deforestation (DETER) in 2004. Developed and operated by INPE, DETER is a satellite-based system that captures and processes georeferenced imagery on forest cover. The images, generated in 15-day intervals, are used to locate deforestation hot spots and issue alerts signalling critical areas. The Brazilian Institute for the Environment and Renewable Natural Resources (Ibama), which operates as the national environmental police and law enforcement authority, targets law enforcement activities in the Amazon based on these alerts. Prior to the activation of DETER, Amazon monitoring depended on voluntary reports of deforestation activity, seldom allowing law enforcers to reach hot spots in a timely manner. With the adoption of the new remote sensing system, Ibama was able to more closely monitor and more quickly act upon areas with illegal deforestation activity.

The PPCDAm further enhanced command and control capabilities in the Amazon by promoting mutual cooperation between different government levels and agencies, such as the MMA and the Ministry of Defence. In addition, starting in the mid-2000s, Ibama sought to improve the qualification of its personnel through the establishment of stricter requirements in its recruitment process, leading to an increase in both the number and quality of monitoring personnel. Combined, these changes allowed for more active Amazon monitoring and law enforcement.

Parallel to the PPCDAm's command and control efforts, the creation of protected areas gained momentum in the mid-2000s. From 2004 through 2009, the area covered by conservation units of integral protection and sustainable use in the Legal Amazon increased by over 520,000 square kilometers (see Figure 2). By the end of the decade, approximately 43% of Legal Amazon territory was under protection as either conservation units or indigenous lands.

[Figure 2 about here.]

3.2. 2008: Targeting Policy and Enforcing the Law

A combination of institutional changes implemented in late 2007 and throughout 2008 marks the second policy turning point. First, the passing of Presidential Decree 6,321 in December 2007 established the legal basis for singling out municipalities with intense deforestation activity and taking differentiated action towards them. Selected annually based on their recent deforestation history, these municipalities were classified as in need of priority action to prevent, monitor, and combat illegal deforestation. Any Legal Amazon municipality could be added to what became known as the list of "priority municipalities". Exiting this list was conditioned upon a significant reduction of deforestation. Issued in January 2008, MMA Ordinance 28 listed the first thirty-six priority municipalities.

Differential action taken in priority municipalities largely consisted of more rigorous environmental monitoring and law enforcement. Ibama monitored the municipalities more closely and dedicated a larger share of its resources to them. Licensing and georeferencing requirements for rural establishments were harsher in priority municipalities, and, in an effort to identify fraudulent documents and illegal occupations, private land titles were to be revised. Priority municipalities also became subject to a series of administrative measures that, although not officially established through legislation, imposed an additional cost to being in the MMA's priority list. Examples include, but are not limited, a compromised political reputation for mayors of priority municipalities, and economic sanctions applied by agents of the commodity industry.

Second, law enforcement in the Amazon gained important legal support with the passing of Presidential Decree 6,514 in July 2008. The decree reestablished directives for the investigation and penalization of environmental infractions, determining the administrative processes for the application of sanctions in more detail than had been previously incorporated in legislation. This led to an increase in the clarity and speed of such processes. Moreover, the decree regulated the use of both existing and new instruments for the punishment of environmental crimes, including fines, embargoes, seizure and destruction of production goods and material, and arrest. Overall, these measures brought greater robustness and regulatory stability to the administrative processes for the investigation and penalization of environmental infractions.

Finally, a novel approach towards the concession of rural credit was adopted to restrict financial resources for those who did not abide by environmental law. National Monetary Council (CMN) Resolution 3,545, approved in February 2008, conditioned the concession of rural credit in the Amazon Biome upon presentation of proof of borrowers' compliance with environmental legislation and legitimacy of land claims. Exemptions were granted to small-scale producers. All private and public banks, as well as all credit cooperatives, were to implement the resolution's conditions obligatorily starting in July 2008.

As discussed in Section 1, both 2004 and 2008 policy turning points coincide with subsequent decreases in the Amazon deforestation rate (see Figure 1). This pattern suggests that conservation policies introduced starting in 2004 and 2008 helped curb deforestation in the second half of the 2000s. Separating the effects of conservation policies from those of agricultural commodity prices and other potential drivers of the deforestation slowdown, however, remains an empirical challenge.

4. Conceptual Framework

The model presented in this section describes a simplified situation in which a farmer seeking to increase his agricultural production may do so by expanding farmland beyond the limits of his original landholding. It therefore focuses on the extensive margin of agricultural production. In particular, the model shows how conservation policies may influence the farmer's choice of optimal farmland size, as well as his response to changes in agricultural output prices. Implications derived from this conceptual framework guide our empirical investigation of the relationship between agricultural commodity prices, conservation policies, and deforestation.

4.1. Model

Consider a farmer having an endowment of $\overline{T}$ hectares of cleared homogeneous land that may be used for agricultural activities.[7] There is no rental market for land and all area outside the farmer's property is public forest. The expansion of the farmer's agricultural activities beyond his landholding of $\overline{T}$ can therefore only be done at the expense of areas of public forest.

For each hectare of land used beyond $\overline{T}$, in addition to bearing the cost of clearing the new area, the farmer also faces the risk of paying a penalty for having broken the law and illegally cleared forest areas. The stringency of conservation policies determines

[7] In this model, the term "agricultural activities" refers to the cultivation of cropland, the use of land as pasture for livestock, or a combination of both.

the magnitude of this penalty. We express the shadow cost of expanding farmland beyond $\overline{T}$ as $\Gamma > 0$, which represents the combination of clearing costs and expected monetary infringement costs associated with the illegal use of areas of public forest. Hence, Γ is the model's policy stringency parameter.

Agricultural output is determined by the production function $Y = AT^{\beta}$, where T is farmland A is a productivity parameter. Returns to scale are decreasing ($\beta < 1$). We assume there are non-scalable inputs such as managerial resources. Given the expected price of agricultural output, p, the farmer chooses farmland size to maximize his end-of-season profit, which is defined by:

$$\pi(p, \overline{T}, \Gamma) = \begin{cases} pAT^{\beta} - T & \text{if } T^* \leq \overline{T} \\ pAT^{\beta} - T - \Gamma(T - \overline{T}) & \text{if } T^* > \overline{T} \end{cases}$$

subject to $T \geq 0$. The price of a hectare of farmland is normalized to 1 for $T^* \leq \overline{T}$, and is interpreted as the per hectare cost of capital and labor-related inputs that are assumed to be employed at fixed proportions. For $T^* > \overline{T}$, the price of a hectare of farmland increases to $(1 + \Gamma)$ due to clearing and infringement costs.

Considering only internal solutions ($T^* > 0$), the farmer's optimal choice of farmland is given by:

$$T^* = \begin{cases} (\beta p A)^{\frac{1}{1-\beta}} < \overline{T} & \text{if } p < \overline{P_1} \\ \overline{T} & \text{if } \overline{P_1} \leq p \leq \overline{P_2} \\ \left(\dfrac{\beta p A}{1 + \Gamma}\right)^{\frac{1}{1-\beta}} > \overline{T} & \text{if } p > \overline{P_2} \end{cases} \tag{1}$$

where $\overline{P_1} \equiv \dfrac{\overline{T}^{1-\beta}}{\beta A}$ and $\overline{P_2} \equiv \dfrac{\overline{T}^{1-\beta}(1+\Gamma)}{\beta A} = \overline{P_1}(1 + \Gamma)$.

Equation (1) determines optimal farmland size for different agricultural output price levels. When output prices are relatively low, $p < \overline{P_1}$, part of the farmer's land is left idle, with $T^* < \overline{T}$. For all output price levels between $\overline{P_1}$ and $\overline{P_2}$, optimal farmland size is fixed at $\overline{T}$. The choice of T^* at this concentration point results from the fact that, at $\overline{T}$, the marginal per hectare cost of land discontinuously jumps from 1 to $(1 + \Gamma)$ and remains greater than the marginal revenue up to the point at which output price equals $\overline{P_2}$. Note that the size of the $\overline{P_1}$ to $\overline{P_2}$ price range is proportional to $1 + \Gamma$. Finally, for output price levels above the $\overline{P_2}$ threshold, the farmer chooses to operate beyond $\overline{T}$, which implies clearing $(T^* - \overline{T})$ hectares of public forest. In this case, agricultural output prices are sufficiently high to sustain optimal production at levels of $T^* > \overline{T}$, despite higher production costs.

In the following sections, we examine the model's main policy implications from both theoretical and empirical perspectives.

4.2. Policy Effects on Land Use: Theoretical Implications

In our model's simplified setting, deforestation is defined as the act of clearing areas of public forest to use cleared land for agricultural production. All land beyond the farmer's property (beyond $\overline{T}$) is public forest. Thus, as long as output prices are high enough to induce the clearing of previously unused land, comparative statics for optimal farmland size are analogous to those for deforestation. Policy therefore affects deforestation via its impact on farmland size.

For farmers operating beyond $\overline{T}$, an increase in policy stringency ($d\Gamma > 0$) raises the per hectare cost of farmland and thereby makes production more expensive. Direct effects of an increase in policy stringency on optimal farmland size are formally given by:

$$\frac{dT^*}{d\Gamma} = \begin{cases} 0 & \text{if } p \leq \overline{P_2} \\ -\dfrac{1}{1-\beta}\dfrac{(\beta p A)^{\frac{1}{1-\beta}}}{(1+\Gamma)^{\frac{2-\beta}{1-\beta}}} < 0 & \text{if } p > \overline{P_2} \end{cases} \tag{2}$$

Equation (2) states that when output prices are low ($p \leq \overline{P_2}$), variations in policy stringency do not affect optimal farmland size. This is because relatively low output prices do not encourage the farmer to extend production beyond his landholding ($T^* \leq \overline{T}$). In this case, there is no incentive to clear areas of public forest and therefore no deforestation. However, when output prices are sufficiently high ($p > \overline{P_2}$) and the farmer's optimal choice implies in forest clearings ($T^* > \overline{T}$), stricter policies reduce optimal farmland size. As a result, increased policy stringency alleviates the pressure on public forests and restrains deforestation. Figure 3 illustrates this point graphically.

[Figure 3 about here.]

In addition to its direct effect on optimal farmland size, policy stringency also indirectly impacts deforestation by affecting the relationship between agricultural output prices and optimal land use choices. Indirect effects of an increase in policy stringency on optimal farmland size are formally given by:

$$\frac{d^2T^*}{d\Gamma dp} = \begin{cases} 0 & \text{if } p \leq \overline{P_2} \\ -\dfrac{1}{(1-\beta)^2}\dfrac{(\beta A)^{\frac{1}{1-\beta}}}{(1+\Gamma)^{\frac{2-\beta}{1-\beta}}} p^{\frac{\beta}{1-\beta}} < 0 & \text{if } p > \overline{P_2} \end{cases} \tag{3}$$

Equation (3) states that while policy stringency has no effect on the relationship between output prices and optimal farmland size when output prices are low ($p \leq \overline{P_2}$), stricter policies weaken this relationship for sufficiently high output prices ($p > \overline{P_2}$). Figure 3 again illustrates this effect — an increase in policy stringency flattens the curve relating output prices and optimal farmland size for all $p > \overline{P_2}$. Greater policy stringency therefore decreases the elasticity of optimal land use choice with respect to agricultural output prices.

Finally, although policy stringency has no effect on land use when the farmer operates within his landholding ($T^* \leq \overline{T}$), it does affect marginal costs at $\overline{T}$, since $\overline{P_2} = (1 + \Gamma)\overline{P_1}$. Indeed, as policy becomes more stringent, the distance between $\overline{P_1}$ and $\overline{P_2}$ widens. From an economic perspective, this means that greater policy stringency enlarges the discontinuity in per hectare cost of land at the concentration point $\overline{T}$. Thus, by sufficiently driving up the value of the relevant threshold $\overline{P_2}$, stricter policies curb deforestation in a context of high agricultural output prices.

These results are summarized in the following proposition:

Proposition 1. *The impact of conservation policies on optimal land use choices and deforestation depends on agricultural output price levels. If output prices are low ($p \leq \overline{P_2}$), there is no deforestation and policies do not affect optimal farmland size. If output prices are high ($p > \overline{P_2}$), farmers clear areas of public forest to expand production beyond their landholding — in this case, policies exert both a direct and an indirect effect on optimal farmland size and, thus, on deforestation. Increased stringency of conservation policies will therefore:*

1. *Reduce optimal farmland size,*
$$\frac{dT^*}{d\Gamma} < 0 \text{ if } p > \overline{P_2} \text{ (or } T^* > \overline{T}\text{), and } \frac{dT^*}{d\Gamma} = 0 \text{ otherwise;}$$
and
2. *Weaken the relationship between agricultural output prices and forest clearings,*
$$\frac{d^2T^*}{d\Gamma dp} < 0 \text{ if } p > \overline{P_2} \text{ (or } T^* > \overline{T}\text{), and } \frac{d^2T^*}{d\Gamma dp} = 0 \text{ otherwise.}$$

A simplified summary of comparative statics for the model is presented in Table 1, where each cell relates variations in output prices or policy stringency to the farmer's expected responses in terms of land use, given different output price levels.

[Table 1 about here.]

4.3. Policy Effects on Land Use: Empirical Implications

How can our conceptual framework be used to structure the empirical evaluation of conservation policies? What are the main empirical challenges and possible solutions implied by our model? The theoretical implications discussed in the previous section can be mapped onto empirical implications that help answer these questions. Two of these implications are particularly relevant for our empirical strategy.

First, the model states that agricultural output prices must be included in the analysis of the effects of conservation policies on deforestation. Because variations in output prices affect incentives to clear forest areas, the observed effectiveness of policy will also vary with agricultural prices. In particular, if a new set of policy measures is implemented in a period of decreasing agricultural prices, it may not be possible to capture its effects until prices recover. This is one of the empirical challenges we face when estimating the relative contribution of prices and policies to the recent deforestation slowdown. We must therefore control for agricultural output prices to better identify the policy impact.

This implication also has relevant consequences for the design of public policies. Maintaining a constant (e.g. zero) deforestation rate, for instance, requires command and control efforts to vary in the same direction as agricultural prices.[8] PES policies serve as another example. As the shadow price of preserving the forest varies with agricultural prices, compensation schemes should also vary accordingly.

Second, the model predicts that the effect of conservation policies is influenced not only by agricultural output prices, but also by the relative tightness of land constraints. The smaller the land area that is legally available for use in agriculture within a municipality, the tighter the land constraint faced by farmers, and, thus, the larger the price range within which we observe deforestation in that municipality. In this sense, $\overline{T}$ is a relative measure of land constraint, as it depends on the relationship between legally and illegally available land. Hence, we should explore the tightness of land constraints within our empirical setup as a means of introducing cross-sectional variation in response to policy.

If there is no available data that fully characterizes the extent to which the land constraint is binding at the municipality level, the model suggests two ways in which we can proxy for this tightness. First, we can calculate the ratio between land area that is not legally available for use in agricultural production within a municipality and total municipal land area. This variable depends on the municipality land endowment, a relatively fixed or slow-moving municipality feature. This proxy is valid because, for a given municipality, the

[8] This conceptual framework only considers the simplified case in which the relationship between output prices and agricultural production is contemporaneous. In a richer setting with leads and lags, this implication should be adapted.

greater the calculated ratio, the smaller the relative land area that is legally available for use in agricultural production, and the tighter the relative municipal constraint. Section 5.3 discusses this variable in more detail. Second, we can use observed deforestation during periods of peak prices. This variable depends on conjunctural price fluctuations. Although potentially noisy, this proxy is valid to the extent that, for a given municipality and period, the tighter the land constraint, the higher the incentive to clear new areas as agricultural prices increase.

5. Data and Descriptive Statistics

Our analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. The sample includes municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia.[9] As variation in forest cover is required for the normalization of our main dependent variable (normalized annual deforestation increment — see details of variable construction below), the sample is restricted to municipalities that portray such variation in the sample period. The final sample comprises 380 municipalities. The following sections describe the exercise's main variables and presents descriptive statistics.

5.1. Deforestation

Deforestation data are built from satellite imagery that is processed at the municipality level and publicly released by INPE's Project for Monitoring Deforestation in the Legal Amazon (PRODES). We define deforestation as the annual deforestation increment — the area of forest cleared over the twelve months leading up to August of a given year.[10] The annual deforestation increment of year t therefore measures the area, in square kilometers, deforested between the 1st of August of $t-1$ and the 31st of July of t.

Cloud coverage during the period of remote sensing may limit the satellite's capability to detect land cover patterns, and thus require imagery to be produced at a different time. As a result, image records used to calculate deforestation increments for any given municipality over consecutive years may span from less to more than twelve months. We include

[9] This selection refers to the four states that had at least one of their municipalities classified as a priority municipality in MMA Ordinance 28/2008, and thus accounts for the bulk of 2000s Amazon deforestation. This ensures effects are estimated using data from the region where deforestation activity was most relevant during our period of interest.

[10] We use the municipal deforestation increment because PRODES/INPE does not calculate municipal deforestation rates.

variables indicating cloud coverage and unobservable areas, both made publicly available by PRODES/INPE, in all regressions to control for measurement error.[11]

Sample municipalities exhibit substantial cross-sectional variation in deforestation increment due to heterogeneity in municipality size. We therefore use a normalized measure of the annual deforestation increment to ensure that our analysis considers only relative variations in deforestation increments within municipalities. In doing so, we also address the second empirical implication of our model, which establishes that $\overline{T}$ is a municipality-specific measure of land constraint, as the normalization takes into account the relative nature of $\overline{T}$. The variable is constructed according to the following expression:

$$D_{it} = \frac{ADI_{it} - \overline{ADI}_{it}}{sd\left(ADI_{it}\right)}$$

where D_{it} is the normalized annual deforestation increment for municipality i and year t; ADI_{it} is the annual deforestation increment measured in municipality i between the 1$^{\text{st}}$ of August of $t-1$ and the 31$^{\text{st}}$ of July of t; and $\overline{ADI}_{it}$ and $sd\left(ADI_{it}\right)$ are, respectively, the mean and standard deviation of the annual deforestation increment calculated for each i over the 2002 through 2009 period. The variable ADI_{it} replaces D_{it} in robustness checks to test whether results are driven by the normalization of deforestation increments.

Figure 4 presents municipality-level deforestation figures for 2004 and 2009. The maps show that, although relatively more concentrated in municipalities along the agricultural frontier (a region often referred to as the "Arc of Deforestation"), the reduction in deforestation was observed over large areas in all sample states. The mere size of these areas illustrates the challenge faced by conservation policies.

[Figure 4 about here.]

5.2. Agricultural Output Prices

Agricultural output prices are endogenous to local agricultural production. Figure 5 shows that crop prices collected at the Agriculture and Supply Secretariat of the State of Paraná (SEAB-PR) are highly correlated with local crop prices averaged across sample municipalities.[12,13] Hence, we use the Paraná price series as exogenous indicators of local

[11]We use PRODES/INPE terminology in referring to partial cloud coverage as "cloud coverage" and to complete cloud coverage as "unobservable area".

[12]Paraná is a southern Brazilian state. It is not part of the Legal Amazon.

[13]Local crop prices are calculated based on municipality-level quantum and current value of production data from the annual Municipal Crop Survey (PAM). PAM data is collected from self-reported centralized municipal agencies, as opposed to being based on on-site surveys of rural producers. Although this

market conditions within our empirical context. The set of commodities includes beef cattle, soybean, cassava, rice, corn, and sugarcane.[14]

[Figure 5 about here.]

We use the Paraná price series to build two variables of interest. The first of these variables, an annual index of crop prices, is constructed in three steps. In step one, we construct nominal annual price series by averaging nominal monthly price series for each calendar year and culture. Annual prices are deflated to year 2000 Brazilian reais (the current Brazilian currency) and are expressed as an index with base year 2000.

In step two, we calculate a weighted real price for each of the crops according to the following expression:

$$PPA_{itc} = PP_{tc} * A_{ic,2000-2001} \tag{4}$$

where PPA_{itc} is the weighted real price of crop c in municipality i and year t; PP_{tc} is the Paraná-based real price of crop c in year t expressed as the index with base year 2000; and $A_{ic,2000-2001}$ is the share of municipal area used as farmland for crop c in municipality i averaged over the 2000 through 2001 period.[15] This latter term captures the relative importance of crop c within municipality i's crop production in the years immediately preceding the sample period. It thus serves as a municipality-specific weight that introduces cross-sectional variation in the commodity price series.

In the third and final step, we use principal component analysis on the weighted real crop prices to derive the annual index of crop prices. This technique allows the price variations that are common to the five selected crops to be represented in a single measure. The resulting index of crop prices captures the first principal component of the five weighted real prices. The first column of Table 2 shows the weights on each crop price that yield the first principal component used in the analysis. The first principal component explains approximately 38% of the variation in the series, driven mostly by soybean, rice, and corn. As the index maximizes the price variance captured by our variable of interest, it represents a more comprehensive measure of the agricultural output price scenario within our empirical setup than the individual prices themselves.

introduces known limitations regarding accuracy of data, PAM is currently the only available source of annual information on agricultural production at the municipality level in Brazil.

[14] Soybean, cassava, rice, and corn are predominant crops in terms of harvested area in the Legal Amazon. Sugarcane is included to account for potential concerns regarding the recent expansion of Brazilian ethanol biofuel production. Together, the five crops account for approximately 70% of total harvested area averaged across sample years.

[15] PAM provides the data on annual municipal harvested area.

[Table 2 about here.]

The second variable of interest is an annual index of cattle prices, which is derived analogously to PPA_{itc} in Equation 4. However, as annual data on land pasture is not available, the index uses the ratio of heads of cattle to municipal area in municipality i averaged over the 2000 through 2001 period as the municipality-specific weight $A_{ci,2000-2001}$.

The use of the annual indices of agricultural prices addresses our model's first empirical implication, which establishes that agricultural output prices should be included in conservation policy evaluation.

5.3. Policies

Two key elements guide the construction of our policy variable. First, the two policy turnings points, which triggered significant changes to Brazilian conservation policy. We interpret these changes as discontinuous increases in policy stringency — one occurring in 2004 and the other in 2008 — that ultimately increased the cost of deforestation. Second, how tight farmers are within their landholdings. According to our conceptual framework, we assume that conservation policies are binding when optimal farmland size exceeds that of the farmer's landholding. If all farmers (and their respective landholdings) operating within a municipality are aggregated, the model's reasoning can be extended to the municipal level. Conservation policies should be binding, and thus potentially effective, in municipalities where agricultural land constraints are tight.

In light of these two elements, we construct policy variables based on interactions between: (i) the 2004 and 2008 turning points, represented by the dummy variables $Post2004 = \mathbf{1}(year > 2004)$ and $Post2008 = \mathbf{1}(year > 2008)$; and (ii) a proxy for the tightness of municipal land constraints, which introduces cross-sectional variation in our policy variables. Since deforestation in the Brazilian Amazon is measured within the 12-month window leading up to August of each year, the policy variables are constructed to match the timing of changes to environmental regulations starting in the second semester of 2004 (2008).

We build our main proxy for the tightness of municipal land constraints based on our conceptual model's empirical implications (see Section 4.3). This proxy measures the land area that is not legally available for agricultural production (land beyond $\overline{T}$ in our model's terminology) as a share of total municipal land area. Essentially, this proxy captures how constrained farmers in a given municipality actually are. If the area they can legally deforest for production is relatively small, land constraints are tight — i.e., $\overline{T}$ is relatively small. In this case, farmers have a smaller area within which to legally expand production in response to agricultural output price increases, and are thus more likely to illegally deforest when agricultural prices are high. Hence, the tighter the municipal land constraint, the greater the chance that conservation policies are binding in a context in which these policies increase the cost of illegally clearing forest area.

We use data from the 2006 Brazilian Agricultural Census to estimate the tightness of municipal land constraints in our sample.[16] We are interested in measuring tightness as defined below:

$$Tight_i = \frac{Vegetation_i + LR_i + APP_i + Unsuitable_i}{MunicipalArea_i - Hydro_i} \quad (5)$$

where $Tight_i$ is the tightness of the land constraint in municipality i. Figure 6 provides a graphical representation of the variables used to define the proxy $Tight_i$ in Equation (5). $Vegetation_i$ is the total area covered by native vegetation in public lands, which includes territory under protection as conservation units or indigenous lands. LR_i is the total area maintained as Legal Reserve inside private properties, while APP_i is total Area of Permanent Protection inside private properties in municipality i.[17,18] $Unsuitable_i$ is the total area that is unfit for agricultural production inside private properties, such as degraded land, constructions, and land that is not viable for agricultural use. $MunicipalArea_i$ is the total area of municipality i. $Hydro_i$ is the total area covered by hydrographic features in municipality i.[19] Note that the numerator measures the total area that is unavailable for agricultural production, be it because it is illegal to deforest these areas, or because these areas are unfit for agricultural use.[20] According to our conceptual model, this is defined by

[16]Ideally, the proxy variable for tightness of municipal land constraint should be constructed using data collected before the sample period to ensure these data, and thereby the proxy variable, had not been affected by potential price or policy effects in early sample years. Unfortunately, the data required to construct our first proxy variable for tightness of municipal land constraint can only be extracted from the 2006 Brazilian Agricultural Census, which collected information on a variety of variables that had not been included in earlier censuses.

[17]Legal Reserves in Brazil are determined such that private landholdings located within the Amazon Biome are required to maintain at least 80% of their total area covered by native vegetation, and private landholdings located inside the Legal Amazon but within the Cerrado Biome are required to maintain at least 50% of their total area covered by native vegetation. If farmers typically held an excess of Legal Reserve, they could perhaps respond to commodity price increases by legally expanding agricultural land. Yet, Legal Reserves on average account for less than 20% of landholdings in our sample. In addition to signaling that landowners are not compliant with environmental regulation in the Amazon, this validates the inclusion of total area occupied by Legal Reserves in our proxy for the tightness of land constraints.

[18]Areas of Permanent Protection are areas inside private property that must be kept covered by native vegetation at all times, such as river margins. These are not to be confused with conservation units or indigenous lands, which are considered protected areas in the Amazon, but are not inside private property.

[19]We deduct the area covered by hydrography from total municipal area because bodies of water do not constitute land area.

[20]Although Legal Reserves and Areas of Permanent Protection are located inside private property,

land beyond $\overline{T}$. Thus, $Tight_i$ measures the share of land that is not legally available for use in agricultural production in each municipality. The larger the value of $Tight_i$, the smaller the relative size of legally available land ($\overline{T}$), the tighter the municipal land constraint.

[Figure 6 about here.]

Data limitations, however, prevent us from constructing the proxy for tightness of land constraint as stated in Equation (5). In particular, $Vegetation_i$ is not observed in the Agricultural Census. In practice, we construct the variable as follows:

$$Tight_i = \frac{(MunicipalArea_i - Hydro_i - Landholding_i) + (LR_i + APP_i + Unsuitable_i)}{MunicipalArea_i - Hydro_i} \tag{6}$$

where $Landholding_i$ is the total area of private properties in municipality i; and all other variables are defined as in Equation (5). Here, the area covered by native vegetation is measured as the difference between total municipal land area and the total area of private landholdings. Because Legal Reserves, Areas of Permanent Protection, and areas unfit for agricultural use — all of which increase the tightness of land constraints — refer to areas within private landholdings, we must add them back in our numerator. Figure 6 shows that Equations (5) and (6) are indeed equivalent in terms of capturing the relative size of $\overline{T}$.

We also use the normalized annual deforestation increment for municipality i in $t = 2004$, $D_{i,2004}$, as an alternative proxy for the tightness of municipal land constraints. This proxy is also suggested by our conceptual framework. Recall that our model implies that farmers will respond to rising agricultural output prices by expanding farmland, and that sufficiently high prices ($p > \overline{P_2}$) will push optimal farmland beyond private landholdings ($\overline{T}$), driving deforestation. Observed deforestation behavior can therefore reflect underlying tightness of land constraints. As the 2004 deforestation increment refers to the 2003 peak in agricultural commodity prices, $D_{i,2004}$ captures how binding municipal land constraints were in 2004, or how close farmers were to $\overline{T}$ at the time. Because this alternative proxy variable depends on conjunctural price fluctuations, which are potentially noisy and can introduce measurement error, we restrict its use to robustness checks.

The final policy variables are given by $Tight_i * Post2004$ and $Tight_i * Post2008$ in main specifications, and by $D_{i,2004} * Post2004$ and $D_{i,2004} * Post2008$ in some robustness checks. It should be noted that $Tight_i$ is built from either fixed or slow-moving variables

Brazilian environmental law determines that it is illegal to clear native vegetation in these areas.

at the municipality level. The interaction of $Tight_i$ with the policy turning points thus results in policy variables that exhibit sharp time and cross-sectional exogenous variation in our municipality-by-year panel. We argue that, conditioned upon high-frequency variation in market forces, municipality fixed-characteristics, municipality-specific time trends, and common time trends, the variation captured by our policy variables should be orthogonal to any latent determinant of deforestation in our empirical setting. As previously argued, this hypothesis is consistent with recent studies on how policy affects deforestation that also assume impacts vary by location due to differences in baseline deforestation that are driven by location-specific characteristics, such as Pfaff and Robalino (2012).

6. Empirical Model

Our empirical strategy follows a fixed-effects model based on a panel of annual data at the municipality level. The benchmark specification is defined by:

$$\begin{aligned} D_{it} = &\alpha_i + \phi_t + M'_{it}\beta_1 + \beta_2 P_{i,t-1} + \\ &\beta_3(Tight_i * Post2004) + \beta_4(Tight_i * Post2008) + X'_{it}\beta_5 + \epsilon_{it} \end{aligned} \tag{7}$$

where D_{it} is the normalized deforestation increment in municipality i between the 1$^{\text{st}}$ of August of $t-1$ and the 31$^{\text{st}}$ of July of t. The first two terms on the right-hand side of Model (7) are municipality and year fixed effects that control for unobservable fixed municipality characteristics and common time trends, respectively. To strengthen the control for municipality-specific time trends, we introduce a separate time trend for each municipality in the sample, M_{it}.

The term $P_{i,t-1}$ includes lagged values for both the annual index of crop prices and the cattle price index, as defined in Section 5.2. We use lagged price indices to account for the timing of agricultural production in the Legal Amazon. The regional dry season usually lasts from June through September. Crops are sown from October through December, and harvested from January through May of the following year. We assume that, aiming at maximizing their expected end of season profits, farmers use prices observed during the early months of $t-1$ to decide the size of the area to be sown and harvested starting in mid-$t-1$. Prices in $t-1$ should thus be associated with forest areas cleared between August of $t-1$ and July of t. We also include the cattle price index calculated for the first six months of t as an additional control to account for potential cattle ranching cycles. This issue is further discussed in Section 7.1.

As $P_{i,t-1}$ is based on an interaction between price trends and municipality farmland before 2002, the coefficient β_2 captures the exogenous effect of variations in the price indices on the municipal deforestation increment from 2002 through 2009. The policy variables $Tight_i * Post2004$ and $Tight_i * Post2008$ absorb the remaining within-municipality variation in the deforestation increment between the years before 2004 (or 2008) and those afterwards. The interaction introduces cross-sectional heterogeneity in tightness of land constraints to address our model's implication that conservation policies will only exert an effect over farmers for whom the land constraint is binding.

Our empirical model relies on the identification hypothesis that β_3 and β_4 capture the effects of increases in policy stringency on deforestation once agricultural commodity prices and municipality time trends have been controlled for. The observed variation in $Tight_i$ across municipalities gives us a baseline for comparison among municipalities that are more or less prone to respond to variations in conservation policy stringency from either 2004 or 2008 onwards. Formally, Model (7) tests whether, after the 2004 and 2008 policy turning points, deforestation declined relatively more in municipalities where land constraint was tighter, conditional not only on agricultural output price trends at the municipality level, but also on common and municipality-specific time trends, as well as on municipality fixed effects.

We also investigate the impact of interactions between the annual index of crop prices and policy variables to test whether policy influences the relationship between agricultural prices and deforestation. As discussed in Section 4.2, we expect policy stringency to affect this relationship by lowering the price elasticity of optimal farmland size when production is set beyond $\overline{T}$.

All regressions include a vector of control variables, X_{it}, containing municipality-level information on cloud coverage and unobservable areas during the period of remote sensing. Note that several potential determinants of deforestation discussed in the literature (population, infrastructure, roads, climate, soil quality, among others — see Section 2) exhibit little to none annual variation at the municipality level. We argue that their impacts on deforestation are captured by the combination of our full set of municipality and year fixed effects with municipality-specific time trends. Finally, robust standard errors are clustered at the municipality level to account for serial correlation in error terms.

7. Deforestation Slowdown: Prices or Policies?

This section presents our three main sets of empirical results. First, we discuss the effects of crop and cattle prices on deforestation. Second, we test whether conservation policies have affected the pace of forest clearings in the Legal Amazon, controlling for agricultural output prices and municipality-specific time trends. Finally, we use regression-based counterfactual simulations to quantify the contribution of conservation policies to the 2000s deforestation slowdown in terms of avoided forest clearings and associated carbon dioxide emissions.

7.1. The Effect of Crop and Cattle Prices on Deforestation

Table 3 presents the relationship between deforestation and both crop and cattle price indices (henceforth referred to as crop prices and cattle prices, respectively). Column 1 shows a positive and robust relationship between crop prices and deforestation. The estimated coefficient 0.229 indicates that a one standard deviation increase of in this variable leads to a 0.31 standard deviation increase in municipality deforestation (the standard deviation of the price index is 1.37). We also find a heterogeneous relationship between cattle prices and deforestation in column 1. Current variations in cattle prices are negative and significantly associated with deforestation, while the relationship between lagged prices and deforestation is positive and significant.

[Table 3 about here.]

This pattern of behavior for cattle prices and deforestation agrees with models of cattle cycles under fairly general conditions. Beef cattle stocks have been placed among the most periodic time series in economics. The explanation for this is that cattle are both capital and consumption goods. Some analysts suggest the existence of a negative supply response in animal industries (Jarvis, 1974; Rosen et al., 1994). For instance, if the price increase is sufficiently permanent, producers may optimally retain a larger number of females to add to the breeding stock so as to take advantage of higher prices in the future. On the other hand, a temporary demand shock leading to an increase in beef cattle prices should drive a positive short run supply response by cattle producers. The response in terms of increasing slaughter would therefore lower the pressure on land use and new forest clearings. In fact, a positive supply response can be derived even under permanent price shocks once the beef cattle industry is modeled in a more general framework. Aadland and Bailey (2001), for instance, allow producers to make decisions in different margins. The authors show that producers will respond positively to relatively higher prices along the consumption margin (increasing heifer cull rates) and will build up stocks along the investment margin (retaining females). These dynamics are therefore much in line with the relationship we find between cattle prices and deforestation. While a positive shock to lagged annual cattle prices could lead to increases in both heifer and cow inventories (and more pressure towards forest clearings), positive shocks to current prices could raise heifer cull rates and lower the pressure on land use.

In columns 2 through 4, we explore the relationship between deforestation and the timing of the variations in crop prices. In column 2, we use the annual index of crop prices calculated only for January through May of $t-1$. This variable captures the variation in crop prices before the dry season. In column 3, we include the index calculated only for the $t-1$ dry season months, June through September. Finally, in column 4, index calculation is restricted to the $t-1$ sowing period, October through December. We find that deforestation is positively and significantly associated with variation in prices during only the first two periods (columns 2 and 3). This result is consistent with our hypothesis that farmers make decisions about land use and forest clearings before the sowing period. In Section 8, we discuss the potential caveats associated with this result and perform robustness checks. Placebo tests confirm that we are accurately capturing the timing of the relationship between crop prices and deforestation.

Finally, the last columns of Table 3 use the culture-specific crop price indices defined in Equation (4) as regressors. We find positive and robust associations between deforestation and soybean, rice, and corn prices. There is no significant relationship between deforestation and sugarcane prices, while the coefficient for cassava prices is negative and robust. This latter result can be explained if we take cassava production as an outside option for rural workers and small-scale farmers. Cassava is mostly supplied for domestic, local consumption. Under the hypothesis that cassava prices raise the average rural wage in local labor markets, labor supply shifts driven by higher cassava prices may increase production costs in large-scale plants and thus decrease their pressure for land use in forest areas.

7.2. The Effect of Policies on Deforestation

In column 1 of Table 4, we regress the normalized deforestation increment on the policy variables $Tight_i * Post2004$ and $Tight_i * Post2008$, conditional on agricultural prices and the full set of fixed effects. We find a significant drop in deforestation associated with the 2004 policy turning point, and a less significant, but positive, association between deforestation and the 2008 turning point. In column 2, we control for municipality-specific time trends. As a result, we see a sharp increase in the magnitude of the effect associated with the 2004 turning point. The coefficient of the 2008 policy variable is now also negative and statistically significant. Both effects are large in magnitude — for a municipality at the median of the distribution of $Tight_i$, the estimated drop in deforestation associated with the 2004 policy turning point is approximately 1.2 standard deviation points of the deforestation increment, while the 2008 policy turning point is associated with an impact of 0.7 standard deviation points. Note that the possibility of there being a localized trend of growing deforestation (such as the expansion of the agricultural frontier), particularly after 2008 as commodity prices increased, reinforces the case for including the municipality-specific time trends. These controls ensure the separation of the effect of policies from that of prices, particularly during the period of recovering agricultural prices. The stronger policy effects conditional upon the inclusion of municipality-specific time trends are therefore to be expected.

[Table 4 about here.]

In the following columns of Table 4, we add interactions between policy variables and crop prices. We are now controlling for different sources of price variations and potential heterogeneity in policy effectiveness. In short, we allow policies to affect deforestation responses to prices, as implied by our model. Our conceptual framework suggests that policy stringency affects the relationship between prices and land use by lowering the elasticity of optimal farmland size with respect to prices whenever land constraints are tight. Column 5 shows the results for our most complete specification. Indeed, we find negative coefficients in the triple interactions between $Tight_i$, $Post2004$ (or $Post2008$), and the crop price index. However, the statistical significance of these results does not hold.

Overall, the results obtained thus far indicate that the conservation policies adopted beginning in 2004 and 2008 appear to have been effective in restraining deforestation in the Legal Amazon. Robustness checks in Section 8 provide further support for this result. In particular, we find that the results are robust to using alternative proxy variables for $Tight_i$ and placebo price variables.

7.3. Counterfactual Simulations

We use counterfactual simulations to quantify the contribution of conservation policies to the 2000s Amazon deforestation slowdown in terms of avoided forest clearings and associated carbon dioxide emissions. Our baseline specification is the one presented in column 5 of Table 4, which includes the full set of fixed effects, municipality-specific time trends, and price interactions. This specification delivers the predicted trend in deforestation increment for each sample municipality, as defined by:

$$\begin{aligned}\widehat{D}_{it} = \widehat{\alpha}_i + \widehat{\phi}_t + M'_{it}\widehat{\beta}_1 + \widehat{\beta}_2 P_{i,t-1} + \widehat{\beta}_3(Tight_i * Post2004) \\ + \widehat{\beta}_4(Tight_i * Post2008) + X'_{it}\widehat{\beta}_5 + I'_{it}\widehat{\beta}_6\end{aligned} \quad (8)$$

where $\widehat{D}_{it}$ is the predicted deforestation increment, calculated by using the estimated coefficients represented by the hatted parameters. The term I_{it} represents the full set of interactions between prices and policies.

Given the hatted parameters, we are able to recalculate each $\widehat{D}_{it}$ under the alternative condition $Post2004 = 0$ and $Post2008 = 0$. This calculation delivers the predicted municipality trend in annual deforestation increment in a hypothetical scenario in which conservation policies introduced starting in 2004 and 2008 were not implemented. We then accumulate $\widehat{D}_{it}$ across all 380 sample municipalities and all sample years to calculate total predicted deforestation in the absence of these policies.

Table 5 shows the total observed deforestation trend for the 2002 through 2009 period, as well as the counterfactual trend for the hypothetical scenario described above. Observed deforestation in sample municipalities totaled 57,100 square kilometers in the states of Pará, Mato Grosso, Rondônia, and Amazonas from 2005 through 2009. We estimate that, had the set of conservation policies introduced beginning in 2004 and 2008 not been adopted, this total would have equaled 130,300 square kilometers. Results therefore suggest that conservation policies avoided over 73,000 square kilometers of forest clearings, or 56% of the deforestation that would have occurred from 2005 through 2009 in the absence of such policies. In a simple first step towards cost-benefit analysis, we estimate that the preserved forest area is equivalent to 2.7 billion tonnes of stored carbons dioxide, and is valued at USD 13.2 billion.[21]

[Table 5 about here.]

Figure 7 plots observed and simulated deforestation trends over the period of interest. The dotted lines give a 95% confidence interval to the simulated trend. Avoided deforestation is estimated at around 12,500 square kilometers per year for 2005 through 2008, and at more than 23,000 square kilometers in 2009. It is also noteworthy that deforestation would have peaked in 2005 if the conservation policies associated with the 2004 turning point had not been implemented. This is consistent with the peak in crop prices observed during the first half of 2004, which could have led to more forest clearings during that year's sowing period and thus raised the accumulated deforestation increment from August 2004 through July 2005. Moreover, the deforestation trend would have bent upward beginning in 2007 in the absence of the conservation policies. This suggests that deforestation would have increased with the recovery of agricultural prices.

[Figure 7 about here.]

7.4. Impacts on Population, GDP and Agricultural Production

In this section we examine whether the conservation policies associated with the two turning points are correlated with other economic variables at the municipality level, such as population, municipal GDP per capita, and agricultural production. We follow our

[21] Estimations are based on conversion factors of 10,000 tC/km^2 (36,700 tCO_2/km^2) and 5 USD/tCO_2, as established in MMA (2011).

benchmark Model (7), but replace the deforestation increments by the following alternative outcome variables: (i) log of municipality population; (ii) log of GDP per capita; (iii) ratio of sowed area to municipality area; (iv) total crop production in 1,000 tonnes; and (v) log of municipality cattle herd.

[Table 6 about here.]

Table 6 presents the results. We find no significant impacts on population trends (column 1), and a positive effect on municipal GDP per capita associated with the 2004 policy turning point (column 2). These results are qualitatively important since they suggest that there has not been any important trade-off between recent conservation policies and local development in the Brazilian Amazon. We further examine this view by focusing on the agricultural sector in the remaining columns. In column 3 we find a negative relationship between relative sowed area and the 2004 policy turning point. The policy change is associated with a decline in the ratio of sowed to municipal area of 2.1 percentage points. Yet, column 4 suggests there is no significant correlation between the 2004 policy turning point and municipality crop production, though the point estimate is also negative. The 2008 policy turning point appears to have had no significant impact on the crop farming sector. For cattle ranching, the 2008 turning point is associated with an increase in the size of municipal cattle herd, but the effect is small considering sample averages. Overall, these results support the view that the deforestation slowdown in the Amazon has occurred in tandem with no major downturns in the agricultural sector.

8. Caveats and Robustness Checks

The empirical strategy behind Model (7) relied on two important identification cornerstones. First, that our strategy adequately controls for direct price effects and municipality-specific time trends. This crucially depends on our understanding of the relationship between price variation, choice of farmland size, and deforestation. Thus far, our analysis has been based on the assumption that farmers take spot prices before the sowing period to choose the season's farmland size and the associated extent of forest clearings. However, whether this timing adequately represents farmers' real behavior in the Amazon region is still subject to further empirical investigation. In Section 8.1, we use placebo tests to check whether we are indeed capturing the relevant relationship between price variations and deforestation.

Second, that we adequately capture the cross-sectional variation in land constraints at the municipality level. Although not directly observed, the tightness of land constraints was proxied in our analysis by the ratio between the land area that is not legally available to farmers for production and total municipal area. This proxy should be valid because, for a given municipality, the greater the calculated ratio, the smaller the relative land area legally available for use in agricultural production, and the tighter the relative municipal land constraints. However, detailed information on land use and landholding sizes is available only from 2006 Brazilian Agricultural Census data, which was collected after the 2004 policy turning point had occurred. Although this proxy depends on the municipality land endowment, a relatively fixed or slow-moving municipality feature, it is not totally free from endogenous variation due to policy effects. We can address this potential source of concern by using the alternative proxy for the tightness of municipal land constraints suggested by our conceptual framework. As discussed in Section 4.3, an increase in agricultural prices will push for larger optimal farmland size, thereby tightening the relative land constraint. In Section 8.2, we explore this by using observed deforestation increments associated with a period of peak prices as an alternative proxy variable for tightness. This proxy is valid under the hypothesis that, for a given municipality and period, the tighter the land constraint, the greater the incentive to clear new areas as agricultural prices increase.

We also test a second alternative proxy for the tightness of municipal land constraints, a dummy variable that flags whether a given municipality is above or below the median value in the distribution of $Tight$. This is a simple binary way of comparing municipalities where land constraints are more or less binding.

We also complement the analysis by replacing the normalized deforestation increment with the deforestation increment in square kilometers in the main specifications. Although noisy due to outliers, the regressions based on this alternative dependent variable yield coefficients that can be directly interpreted in terms of deforested area.

Overall, together with our main results, placebo regressions from Section 8.1 indicate that price effects are being consistently estimated. These results are important since agricultural prices (and, therefore, demand for land) should be seen as the most relevant determinant of land use that varies in high frequency at the local level, over time. Together with municipality and time fixed-effects, local specific-time trends and price effects should determine deforestation trends. The remaining variation in deforestation should therefore be due to policy effects. This interpretation is valid since there is no evidence in support of any other determinants of deforestation in the Brazilian Amazon in such high frequency. The remaining variation in deforestation could be therefore associated with policy efforts. Moreover, Section 8.2 shows that robustness checks based on our alternative proxy variable for tightness provides qualitatively similar results in comparison to our main proxy variable.

8.1. The Timing of Price Variations and Deforestation

In Table 7, we perform placebo tests to further investigate the relationship between the timing of price variations and deforestation rates. The baseline specification is the same as the one used in Table 3, columns 1 through 4. In column 1 of Table 7, we add future $(t+1)$ and past $(t-2)$ crop prices as regressors. As in Table 3, we confirm that deforestation is associated positive and significantly with crop price variations in $t-1$. We find no significant association between deforestation and future or past price variations.

[Table 7 about here.]

In columns 2 through 4, we repeat the analysis for specific periods. As in Table 3, we find that deforestation is positively and significantly associated with variation in crop prices before the sowing season of $t-1$ (columns 2 and 3), while no significant impact is found for crop price variations before the sowing seasons of $t+1$ or $t-2$. In the last column we confirm that price variations during the sowing season are not associated with forest clearings. This set of results is consistent with farmers making decisions on land use and forest clearings just before the sowing season of $t-1$. This indicates that our specifications control for the relevant source of crop price variation.

8.2. Alternative Proxy Variables for Tightness

Column 1 of Table 8 repeats the baseline specification found in column 2 of Table 4. In columns 2 and 3, we replace our baseline proxy variable for tightness with alternative variables.

[Table 8 about here.]

In column 2, our baseline proxy is replaced with a dummy variable indicating municipalities that have tightness measures greater than the median of the baseline proxy variable distribution. In column 3, we replace it with $D_{i,2004}$, the normalized annual deforestation increment for each municipality i in $t = 2004$, as defined in Section 5.3. In columns 4 and 5 we add to specifications in columns 2 and 3, respectively, interactions between policies and prices to control for potential heterogeneities in policy and price effects. We find that the effects associated with the policy variables remain significant in all regressions. Finally, in columns 6 through 8 we use the deforestation increment in square kilometers as the dependent variable to ensure that our results are not driven by the normalization of our dependent variable. Although noisy due to outliers and large municipalities, the results remain robust.

9. Final Comments

Understanding the determinants of deforestation and disentangling their specific impacts is a non-trivial task. This paper takes a step in this direction, assessing the causal link between the implementation of new conservation policies and the recent deforestation slowdown in the Brazilian Amazon. Our results suggest that changes to Brazilian environmental policies had a sizeable direct impact on deforestation levels and have thereby curbed forest clearings. This finding is derived from an empirical strategy that controls for different sources of price variations, common time trends, and municipality-specific fixed characteristics and time trends.

The baseline simulation indicates that conservation policies avoided over 73,000 square kilometers of deforestation in the 2005 through 2009 period. This represents more than half of the forest area that would have been cleared had the policies not been introduced. This is equivalent to an avoided loss of 2.7 billion tonnes of stored carbon dioxide and is valued at USD 13.2 billion.

We also extract an important lesson for PES policy design from the empirical finding that agricultural output prices are relevant drivers of Amazon deforestation. PES compensation schemes should incorporate output price variations to ensure producers' incentives are, at all times, aligned with the preservation of natural capital. We therefore contribute with new evidence to an existing core debate about PES efforts. This issue lies at the core of the recent debate about PES efforts (Angelsen and Wertz-Kanounnikoff, 2008; Angelsen, 2010; Alston and Andersson, 2011; Robalino and Pfaff, 2013). Although the implementation of PES often occurs in a context different to the one assessed in this paper, our results highlight the importance of sustained monitoring and enforcement of conditionalities for PES, in particular in a scenario of increasing agricultural prices.

Overall, our results show that: (i) deforestation is indeed responsive to agricultural output prices; (ii) changes to conservation policies implemented beginning in 2004 and 2008 significantly contributed to the curbing of deforestation, even after controlling for a variety of price effects; and (iii) counterfactual simulations suggest that the policies beginning in 2004 and 2008 avoided substantial Amazon deforestation from 2005 through 2009.

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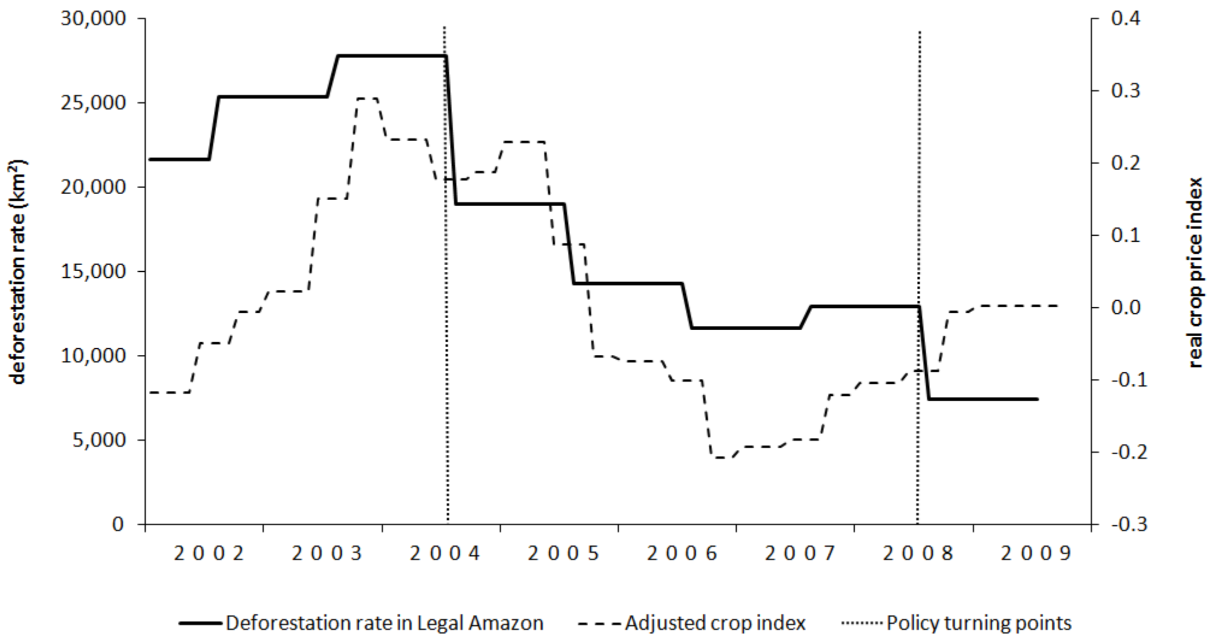
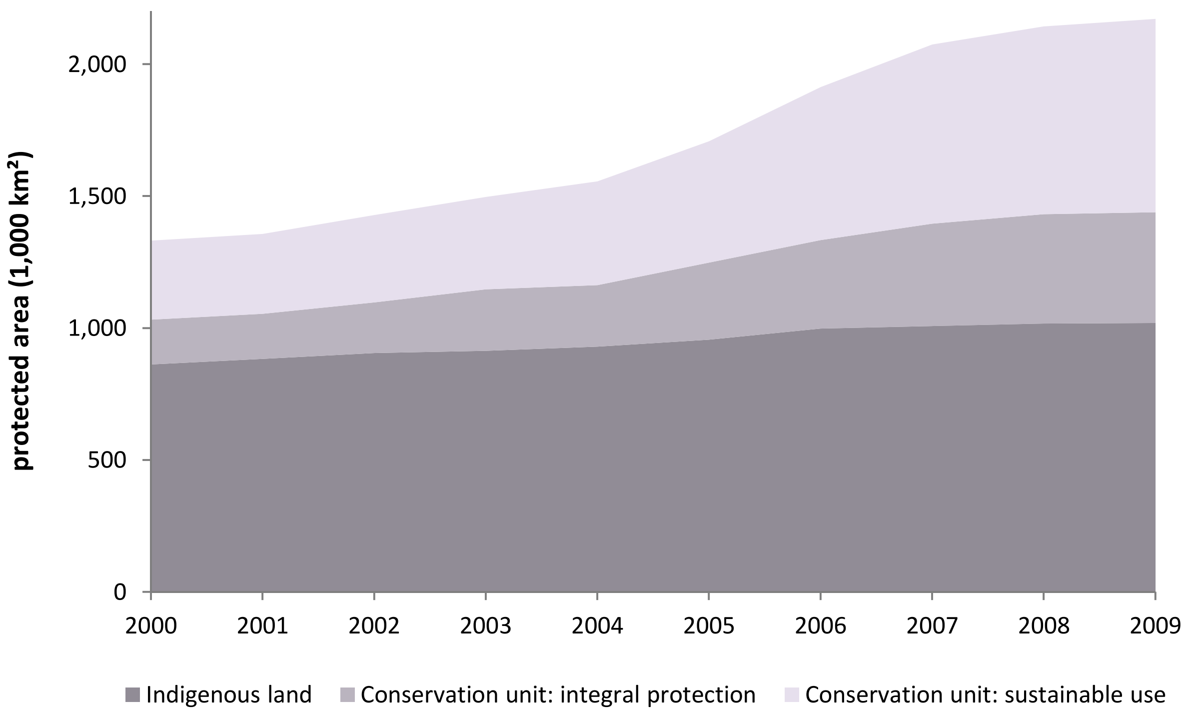
Figure 1: Amazon Deforestation Rate and Agricultural Price Trends, 2002-2009



Notes: The deforestation rate measures the rate of forest clearings from August of year t-1 through July of year t. The adjusted crop price index plots the first principal component of the variations in real prices for soybean, cassava, rice, corn, and sugarcane. Each year contains data for a January through May (harvest season) average; June through September (dry season) average; and October through December (sowing season) average. The policy turning points mark the timing of relevant changes in the direction of Brazilian environmental policy (see Section 3 for a detailed description).

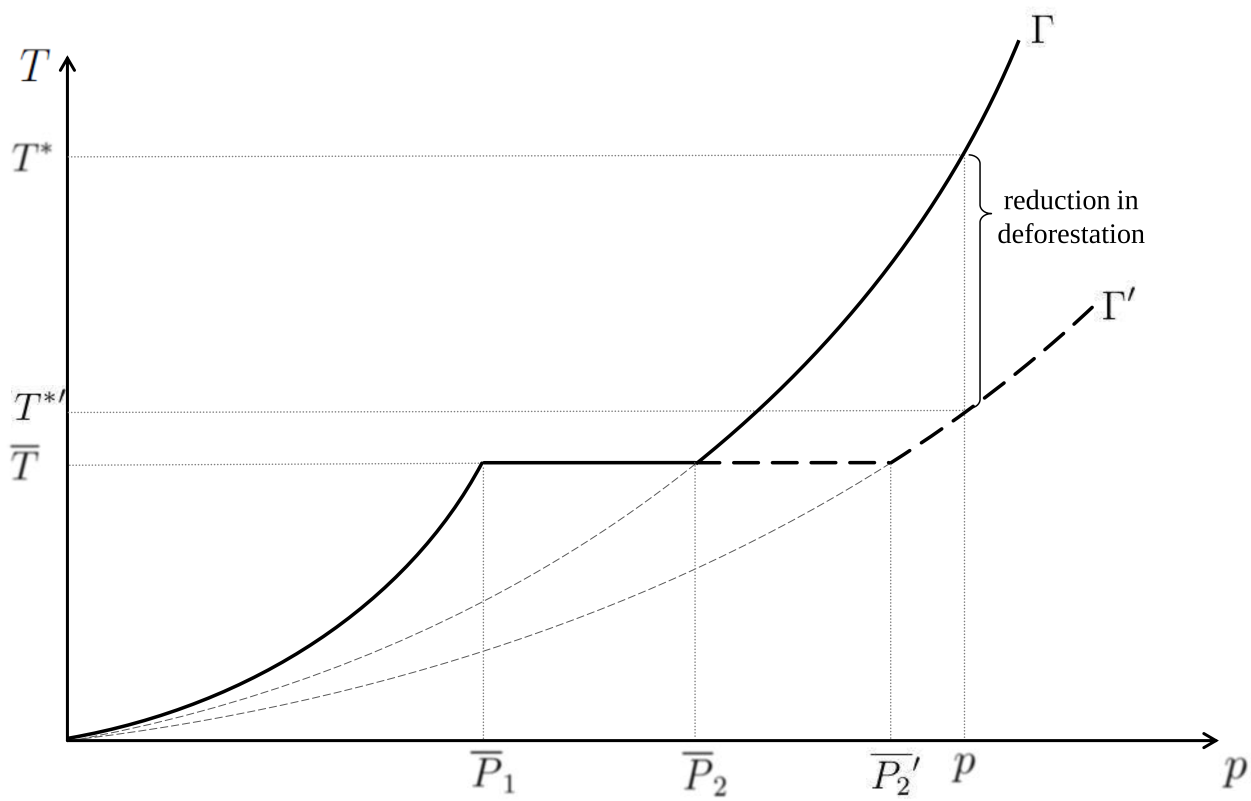
Source: data from PRODES/INPE (deforestation) and SEAB-PR (commodity prices).

Figure 2: Legal Amazon Protected Territory by Type, 2000-2009



Source: data from the National Registry of Conservation Units (CNUC/MMA) and the National Indigenous Peoples Foundation (FUNAI).

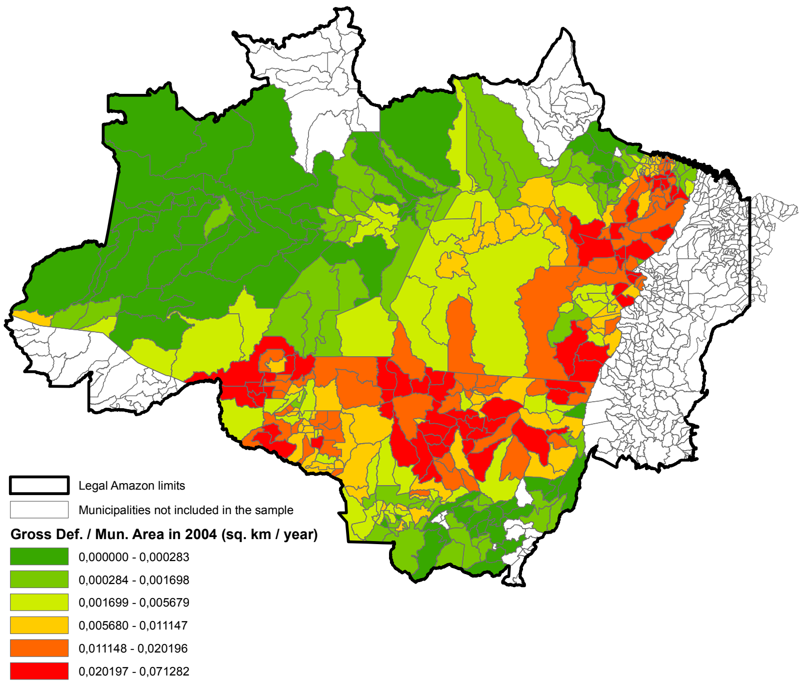
Figure 3: Comparative Statics — Policy Effect on Optimal Farmland Size



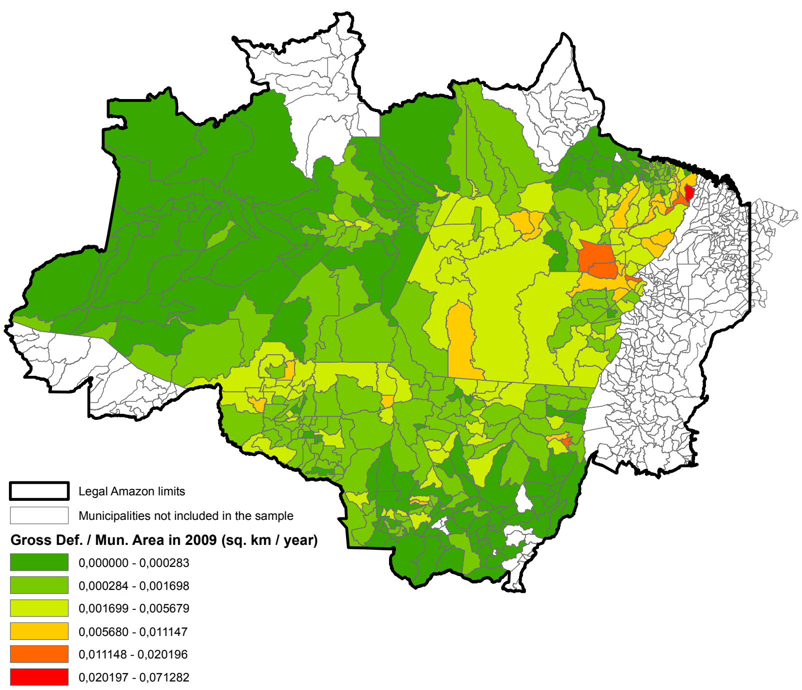
Notes: the graph illustrates a producer's optimal farmland choice (T^*) given agricultural output prices (p) under a shift from less stringent (Γ) to more stringent (Γ') conservation policy.

Figure 4: Gross Deforestation Increment per Municipal Area

(a) 2004



(b) 2009

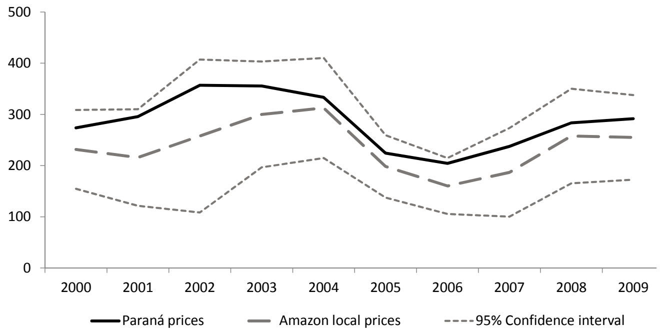


Notes: the maps illustrate municipality-level gross deforestation increment as a share of municipal area.

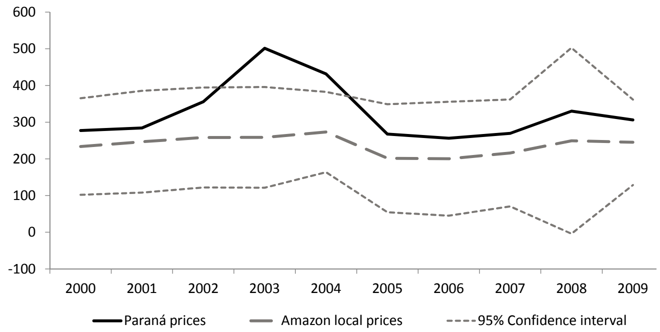
Source: data from PRODES/INPE.

Figure 5: Paraná Price Series and Average Amazon Prices, 2000-2009

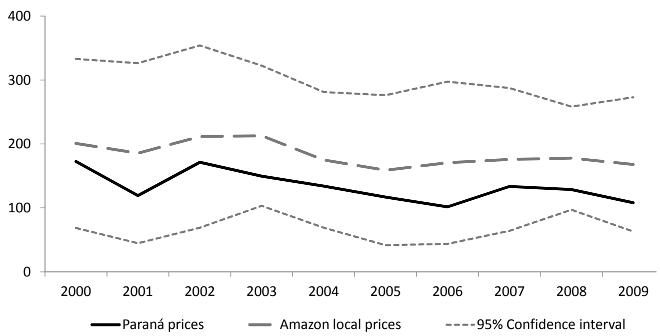
(a) Soybean



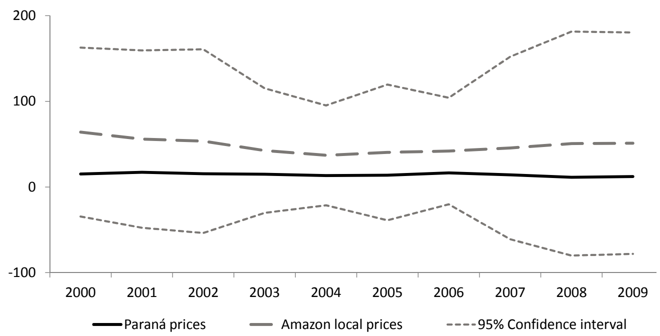
(b) Rice



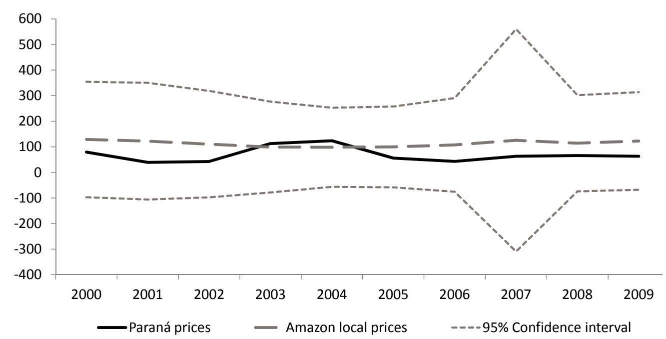
(c) Corn



(d) Sugarcane



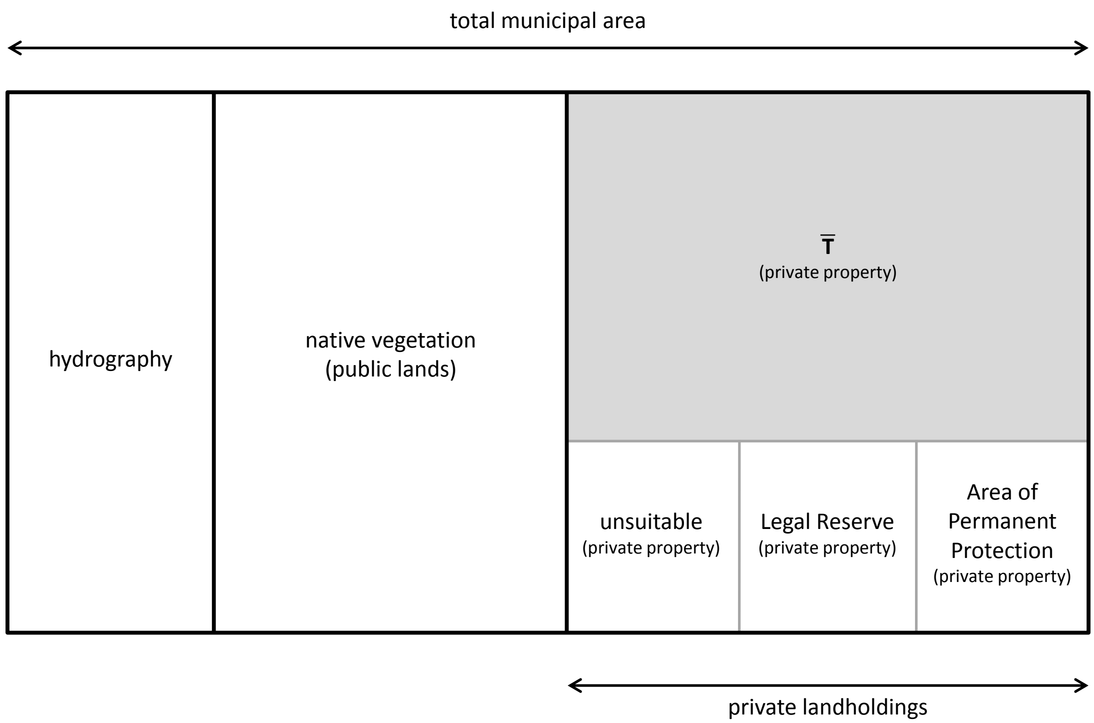
(e) Cassava



Notes: Paraná prices capture agricultural commodity prices from a non-Amazon Brazilian state. Amazon local prices are agricultural commodity prices calculated from municipality-level production data averaged across sample municipalities.

Source: data from SEAB-PR and PAM.

Figure 6: Variable Construction — Proxy for Tightness of Land Constraint



Notes: the figure illustrates the construction of the proxy variable for tightness of municipal land constraints. Note that Legal Reserves, Areas of Permanent Protection and areas unsuitable for agricultural use are all inside private landholdings. We assume, as in our model, that all land beyond $\overline{T}$ is public forest.

Figure 7: Counterfactual Simulation - What Would Have Happened in the Absence of the Policy Change?

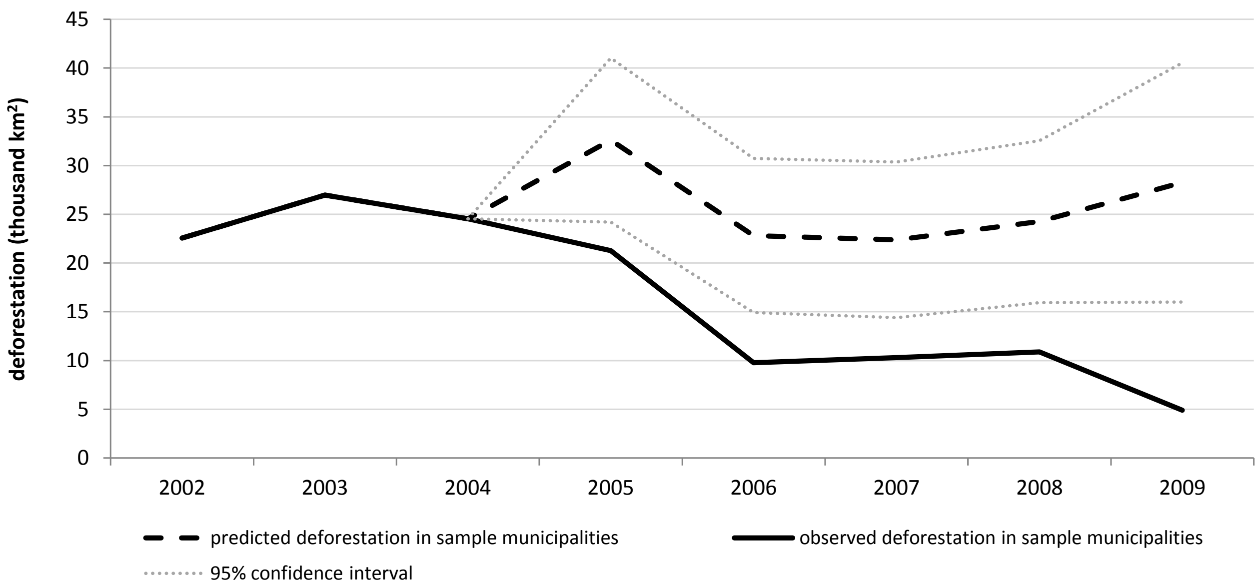


Table 1: Output Price and Policy Effects on Optimal Farmland Size

	Optimal Farmland Size (T^*)		
	$p < \overline{P_1}$	$\overline{P_1} \leq p \leq \overline{P_2}$	$p > \overline{P_2}$
Price (dp)	+	0	+
Policy ($d\Gamma$)	0	0	–
Price*Policy ($dpd\Gamma$)	0	0	–

Notes: the table presents comparative statics for output price and policy effects on optimal farmland size within the scope of our theoretical model.

Table 2: The Annual Index of Crop Prices and Descriptive Statistics

	Weights of 1^{st} Component of PCA	Sown Area as Share of: Total Municipality Area 2002	2009	Difference	Total Municipality Sown Area 2002	2009	Difference
Soybean	0.5940	0.0147	0.0226	0.0079	0.1076	0.1549	0.0474
Rice	0.4879	0.0041	0.0028	-0.0013	0.2278	0.1578	-0.0700
Corn	0.6362	0.0067	0.0101	0.0034	0.2867	0.2830	-0.0037
Sugarcane	0.0631	0.0022	0.0025	0.0003	0.0339	0.0363	0.0024
Cassava	0.0171	0.0041	0.0047	0.0006	0.3440	0.3680	0.0240

Notes: the table presents descriptive statistics for the constructed annual index of crop prices. Sample includes 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia. Data from SEAB-PR (agricultural prices) and PAM (agricultural production).

Table 3: The Effect of Crop and Cattle Prices on Deforestation

	Annual Normalized Deforestation Increment								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Crop price index (t-1)	0.229								
	(0.069)***								
Crop price index (Jan-May, t-1)		0.196							
		(0.062)***							
Crop price index (Jun-Sep, t-1)			0.223						
			(0.073)***						
Crop price index (Oct-Dec, t-1)				0.061					
				(0.048)					
Soybean price index (t-1)					0.037				
					(0.014)***				
Corn price index (t-1)						0.144			
						(0.067)**			
Sugarcane price index (t-1)							0.037		
							(0.073)		
Rice price index (t-1)								0.204	
								(0.075)***	
Cassava price index (t-1)									-0.102
									(0.042)**
Cattle price index (Jan-Jun, t)	-0.021	-0.020	-0.021	-0.023	-0.023	-0.023	-0.023	-0.019	-0.022
	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***	(0.007)***
Cattle price index (Jan-Dec, t-1)	0.010	0.010	0.010	0.013	0.014	0.012	0.013	0.008	0.013
	(0.006)*	(0.006)*	(0.006)*	(0.006)**	(0.006)**	(0.006)**	(0.006)**	(0.006)	(0.006)**
Observations	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040
Year and municipality fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes	yes	yes	yes	yes	yes

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is the annual normalized deforestation increment at the municipality level. All regressions include year and municipality fixed effects, municipality time trends, and controls for cloud cover and unobservable areas. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4: The Effect of Conservation Policies on Deforestation

	Annual Normalized Deforestation Increment				
	(1)	(2)	(3)	(4)	(5)
Tight * Post2004	-0.594	-1.633	-1.648	-1.592	-1.714
	(0.177)***	(0.363)***	(0.409)***	(0.374)***	(0.415)***
Tight * Post2008	0.413	-0.978	-0.944	-1.176	-1.213
	(0.180)**	(0.326)***	(0.327)***	(0.336)***	(0.340)***
Crop price index (t-1)	0.253	0.279	0.049	0.040	0.043
	(0.053)***	(0.077)***	(0.263)	(0.294)	(0.290)
Cattle price index (Jan-Jun, t)	-0.024	0.005	0.004	0.004	0.004
	(0.006)***	(0.010)	(0.010)	(0.010)	(0.010)
Cattle price index (Jan-Dec, t-1)	0.036	-0.011	-0.008	-0.010	-0.010
	(0.006)***	(0.010)	(0.010)	(0.010)	(0.010)
Tight * Crop price index			0.488	0.592	0.584
			(0.505)	(0.569)	(0.563)
Crop price index * Post2004			0.039		0.043
			(0.148)		(0.145)
Crop price index * Post2008				0.011	0.021
				(0.123)	(0.115)
Tight * Crop price index * Post2004			-0.111		-0.152
			(0.296)		(0.295)
Tight * Crop price index * Post2008				-0.170	-0.208
				(0.242)	(0.234)
Observations	3,040	3,040	3,040	3,040	3,040
Year and municipality fixed effects	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes
Municipality-specific time trends	no	yes	yes	yes	yes

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is the annual normalized deforestation increment at the municipality level. All regressions include year and municipality fixed effects, municipality time trends, and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 5: Counterfactual Simulations - Observed and Predicted Deforestation

Year	Deforestation in Sample Municipalities (in km^2)	
	observed	predicted
2002	22,574	22,574
2003	26,980	26,980
2004	24,526	24,526
2005	21,273	32,610
2006	9,786	22,822
2007	10,304	22,391
2008	10,872	24,246
2009	4,909	28,259
Total deforestation, 2005-2009	57,144	130,328
Avoided deforestation, 2005-2009	-	73,185
Avoided deforestation, 2005-2009 (as % of predicted)		56%

Notes: counterfactual simulation is based on Model (8) and uses the specification presented in column 5 of Table 4, which includes the full set of fixed effects, specific time trends, and price interactions. Analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Regressions include year and municipality fixed effects, municipality time trends, and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 6: Impacts on Population, GDP, and Agricultural Production

	Ln(Population)	Ln(GDP per capita)	Sowed Area / Municipal Area	Production (crops, 1,000t)	Ln(Cattle)
	(1)	(2)	(3)	(4)	(5)
Tight * Post2004	-0.026	0.111	-0.021	-12.378	-0.046
	(0.025)	(0.054)**	(0.008)***	(15.906)	(0.073)
Tight * Post2008	-0.000	0.059	0.009	-11.757	0.196
	(0.014)	(0.045)	(0.007)	(10.156)	(0.096)**
Crop price index (t-1)	0.000	0.120	0.011	21.874	0.004
	(0.005)	(0.025)***	(0.006)*	(6.897)***	(0.022)
Cattle price index (Jan-Jun, t)	0.002	-0.005	0.000	0.147	-0.002
	(0.002)	(0.002)**	(0.000)	(0.379)	(0.003)
Cattle price index (Jan-Dec, t-1)	0.000	-0.000	0.000	-0.517	0.008
	(0.001)	(0.002)	(0.000)	(0.393)	(0.003)***
Mean of dependent variable	9.792	1.224	0.038	74.658	10.685
(2004 coefficient * mean of Tight) / mean of dependent variable	-0.2%	6.0%	-37.0%	-11.1%	-0.3%
(2008 coefficient * mean of Tight) / mean of dependent variable	0.0%	3.2%	15.8%	-10.5%	1.2%
Observations	3,040	3,040	3,040	3,040	3,040
Year and municipality fixed effects	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes	yes

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is: the log of municipal population (column 1); the log of municipal GDP per capita in column 2; the ratio of sowed to municipal area (column 3); total crop production (column 4); the log of head of cattle (column 5). Data from IBGE (population, municipal GDP), PAM (sowed area, crop production), and the Municipal Livestock Survey (PPM) (head of cattle). All regressions include year and municipality fixed effects, municipality time trends and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 7: Placebo Regressions — The Timing of Price Variation and Its Impact on Deforestation

	Annual Normalized Deforestation Increment			
	(1)	(2)	(3)	(4)
Crop price index (t-1)	0.390			
	(0.181)**			
Crop price index (t+1)	-0.027			
	(0.215)			
Crop price index (t-2)	0.066			
	(0.188)			
Crop price index (Jan-May, t-1)		0.228		
		(0.125)*		
Crop price index (Jan-May, t+1)		0.077		
		(0.164)		
Crop price index (Jan-May, t-2)		-0.006		
		(0.136)		
Crop price index (Jun-Sep, t-1)			0.434	
			(0.161)***	
Crop price index (Jun-Sep, t+1)			0.045	
			(0.156)	
Crop price index (Jun-Sep, t-2)			0.188	
			(0.158)	
Crop price index (Oct-Dec, t-1)				0.135
				(0.094)
Crop price index (Oct-Dec, t+1)				-0.139
				(0.159)
Crop price index (Oct-Dec, t-2)				0.101
				(0.117)
Cattle price index (Jan-Jun, t)	-0.112	-0.114	-0.109	-0.113
	(0.022)***	(0.022)***	(0.022)***	(0.022)***
Cattle price index (Jan-Dec, t-1)	0.180	0.185	0.175	0.183
	(0.040)***	(0.039)***	(0.039)***	(0.040)***
Observations	2,280	2,280	2,280	2,280
Year and municipality fixed effects	yes	yes	yes	yes
Controls	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is the annual normalized deforestation increment at the municipality level. All regressions include year and municipality fixed effects, municipality time trends and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.

Table 8: Robustness Checks — Alternative Dependent Variable and Proxy Variables for Tightness

	Annual Normalized Deforestation Increment					Annual Deforestation Increment (in km^2)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Tight * Post2004	-1.633	-0.546	-0.748	-0.529	-0.740	-39.647	-18.744	-16.179
	(0.363)***	(0.151)***	(0.065)***	(0.163)***	(0.069)***	(14.123)***	(8.952)**	(3.745)***
Tight * Post2008	-0.978	-0.293	-0.516	-0.382	-0.533	-36.071	-17.315	-14.180
	(0.326)***	(0.130)**	(0.057)***	(0.139)***	(0.058)***	(10.978)***	(6.689)**	(2.364)***
Crop price index (t-1)	0.279	0.261	0.208	0.272	-0.073	-54.254	-2.685	-16.804
	(0.077)***	(0.074)***	(0.067)***	(0.085)***	(0.135)	(11.922)***	(2.919)	(4.679)***
Cattle price index (Jan-Jun, t)	0.005	-0.007	-0.019	-0.008	-0.017	0.288	0.234	-0.128
	(0.010)	(0.009)	(0.008)**	(0.009)	(0.008)**	(0.285)	(0.269)	(0.206)
Cattle price index (Jan-Dec, t-1)	-0.011	-0.000	0.008	0.001	0.009	-0.290	-0.361	-0.060
	(0.010)	(0.008)	(0.006)	(0.008)	(0.006)	(0.306)	(0.276)	(0.183)
Tight * Crop price index				0.324	0.277	118.275	52.893	
				(0.269)	(0.114)**	(27.388)***	(20.232)***	
Crop price index * Post2004				-0.009	0.177	-0.978	-2.997	-0.909
				(0.049)	(0.107)*	(7.322)	(0.997)***	(1.462)
Crop price index * Post2008				-0.054	0.029	8.217	1.607	5.877
				(0.030)*	(0.044)	(5.217)	(1.420)	(1.740)***
Tight * Crop price index * Post2004				0.024	-0.072	-4.670	-1.960	0.885
				(0.128)	(0.063)	(16.632)	(9.852)	(0.898)
Tight * Crop price index * Post2008				-0.080	-0.018	-15.236	-5.592	-2.042
				(0.114)	(0.026)	(10.714)	(6.128)	(1.055)*
Observations	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040
Year and municipality fixed effects	yes	yes	yes	yes	yes	yes	yes	yes
Controls	yes	yes	yes	yes	yes	yes	yes	yes
Municipality-specific time trends	yes	yes	yes	yes	yes	yes	yes	yes
Robustness	Tight = baseline	Tight = dummy: baseline > median	Tight = 2004 deforestation increment	Tight = dummy: baseline > median	Tight = 2004 deforestation increment	Tight = baseline	Tight = dummy: baseline > median	Tight = 2004 deforestation increment

Notes: analysis is based on a municipality-by-year panel data set covering the 2002 through 2009 period. Sample includes the 380 municipalities located in the Legal Amazon states of Amazonas, Mato Grosso, Pará, and Rondônia, which exhibited variation in forest cover during the sample period. Dependent variable is the annual normalized deforestation increment at the municipality level. All regressions include year and municipality fixed effects, municipality time trends and controls for unobservable areas and cloud cover. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms. Significance: *** p<0.01, ** p<0.05, * p<0.1.