

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 62,000 square kilometers of deforestation, approximately half of total deforestation 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 2.3 billion tonnes of stored carbon dioxide.

Key words: deforestation, conservation policies, agricultural prices, Amazon

JEL: 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 CO₂ 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 CO₂ emissions (MCT (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.

In this paper, we assess 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 size of the landholding that is suitable for production 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. In particular, policies have no effect in places where the size of the landholding that is suitable for production is sufficiently large. Thus, we should expect policies to be effective only 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.

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.¹ Our main dependent variable, the normalized annual deforestation increment, is constructed from satellite-based deforestation data.²

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. 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

¹The 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.

²From the National Institute for Space Research's (INPE) Project for Monitoring Deforestation in the Legal Amazon (PRODES).

legally available to farmers for use in agricultural production relative to total municipal 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 underlying tightness of land constraints, with periods marked by more intense deforestation being indicative of 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 panel of data at the municipality level.

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-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, as implied by our conceptual framework, 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 119,200 square kilometers. Yet, observed sample deforestation in this period totaled 57,100 square kilometers – 52% less than in the absence of the policies. Our results therefore suggest that conservation policies avoided 62,100 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 62,100 square kilometers of avoided deforestation are equivalent to a store of 2.3 billion tonnes of carbon dioxide.³ Given the price of 5 USD/tCO₂ commonly used in current applications, this store is valued at USD 11.5 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 significant impact on population trends and 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 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 (see Angelsen and Kaimowitz (1999) and Barbier

³Estimations are based on a conversion factor of 10,000 tC/km² (36,700 tCO₂/km²), as established in DPCD/MMA (2011).

and Burgess (2001) for comprehensive surveys of the literature).

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 (to name a few, see Cropper and Griffiths (1994), Panayotou and Sungsuwan (1994), Chomitz and Gray (1996), Barbier and Burgess (1996), Cropper et al. (1997), Pfaff (1999), Chomitz and Thomas (2003), and 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 (among others, see Reis and Margulis (1991), Reis and Guzmán (1994), Panayotou and Sungsuwan (1994), Chomitz and Gray (1996), Barbier and Burgess (1996), Pfaff (1999), Pfaff et al. (2007), Araujo et al. (2009), Hargrave and Kis-Katos (2012)).

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. 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. 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 (e.g. Ewers et al. (2008), Mendonça et al. (2012); see Pfaff et al. (2010) 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), Soares-Filho et al. (2010), Sims (2010), Pfaff et al. (2011), Joppa and Pfaff (2011), Nelson and Chomitz (2011), 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. 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), Barbier and Burgess (1996), Andersen (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 (2012)). 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 (2012)), 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 undoubtedly useful to 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.⁴ 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 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 geo-referenced imagery on forest cover. The images, generated in 15-day intervals, are used

⁴The Chief of Staff of the Presidency of the Republic is the highest-ranking member of the Brazilian Executive Office.

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.

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 $\bar{T}$ hectares of cleared homogenous land that may be used for agricultural activities.⁵ 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 $\bar{T}$ can therefore only be done at the expense of areas of public forest.

For each hectare of land used beyond $\bar{T}$, 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 the magnitude of this penalty. We express the shadow cost of expanding farmland beyond $\bar{T}$ 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:

$$\pi(p, \bar{T}, \Gamma) = \begin{cases} pAT^\beta - T & \text{if } T^* \leq \bar{T} \\ pAT^\beta - T - \Gamma(T - \bar{T}) & \text{if } T^* > \bar{T} \end{cases} \quad (1)$$

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

⁵In 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.

is given by:

$$T^* = \begin{cases} (\beta p A)^{\frac{1}{1-\beta}} < \bar{T} & \text{if } p < \bar{P}_1 \\ \bar{T} & \text{if } \bar{P}_1 \leq p \leq \bar{P}_2 \\ \left(\frac{\beta p A}{1 + \Gamma} \right)^{\frac{1}{1-\beta}} > \bar{T} & \text{if } p > \bar{P}_2 \end{cases} \quad (2)$$

where $\bar{P}_1 \equiv \frac{\bar{T}^{1-\beta}}{\beta A}$ and $\bar{P}_2 \equiv \frac{\bar{T}^{1-\beta}(1 + \Gamma)}{\beta A} = \bar{P}_1(1 + \Gamma)$.

Equation (2) determines optimal farmland size for different agricultural output price levels. When output prices are relatively low, $p < \bar{P}_1$, part of the farmer's land is left idle, with $T^* < \bar{T}$. For all output price levels between $\bar{P}_1$ and $\bar{P}_2$, optimal farmland size is fixed at $\bar{T}$. The choice of T^* at this concentration point results from the fact that, at $\bar{T}$, 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 $\bar{P}_2$. Note that the size of the $\bar{P}_1$ to $\bar{P}_2$ price range is proportional to $1 + \Gamma$. Finally, for output price levels above the $\bar{P}_2$ threshold, the farmer chooses to operate beyond $\bar{T}$, which implies clearing $(T^* - \bar{T})$ hectares of public forest. In this case, agricultural output prices are sufficiently high to sustain optimal production at levels of $T^* > \bar{T}$, 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 $\bar{T}$) 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 $\bar{T}$, 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:

$$\frac{dT^*}{d\Gamma} = \begin{cases} 0 & \text{if } p \leq \bar{P}_2 \\ -\frac{1}{1 - \beta} \frac{(\beta p A)^{\frac{1}{1-\beta}}}{(1 + \Gamma)^{\frac{2-\beta}{1-\beta}}} < 0 & \text{if } p > \bar{P}_2 \end{cases} \quad (3)$$

Equation (3) 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.

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:

$$\frac{d^2 T^*}{d\Gamma dp} = \begin{cases} 0 & \text{if } p \leq \overline{P}_2 \\ -\frac{1}{(1-\beta)^2} \frac{(\beta A)^{\frac{1}{1-\beta}}}{(1+\Gamma)^{\frac{2-\beta}{1-\beta}}} p^{\frac{\beta}{1-\beta}} < 0 & \text{if } p > \overline{P}_2 \end{cases} \quad (4)$$

Equation (4) 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 I, 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.

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.⁶ PES policies serve as another example. As the shadow price of preserving the forest varies with agricultural prices, compensation schemes should also vary accordingly.

⁶This 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.

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, $\bar{T}$ 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 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 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.⁷ 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.

⁷This 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.

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.⁸ 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 variables indicating both cloud coverage and unobservable areas, both made publicly available by PRODES/INPE, in all regressions to control for measurement error.⁹

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 $\bar{T}$ is a municipality-specific measure of land constraint, as the normalization takes into account the relative nature of $\bar{T}$. The variable is constructed according to the following expression:

$$D_{it} = \frac{ADI_{it} - \overline{ADI}_{it}}{sd(ADI_{it})} \quad (5)$$

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 1st of August of $t - 1$ and the 31st of July of t ; and $\overline{ADI}_{it}$ and $sd(ADI_{it})$ 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

⁸We use the municipal deforestation increment because PRODES/INPE does not calculate municipal deforestation rates.

⁹We use PRODES/INPE terminology in referring to partial cloud coverage as "cloud coverage" and to complete cloud coverage as "unobservable area".

illustrates the challenge faced by conservation policies.

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.^{10,11} Hence, we use the Paraná price series as exogenous indicators of local market conditions within our empirical context. The set of commodities includes beef cattle, soybean, cassava, rice, corn, and sugarcane.¹²

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:

$$PPA_{itc} = PP_{tc} * A_{ic,2000-2001} \quad (6)$$

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.¹³ This latter term captures the relative importance of crop c within municipality i 's crop production in the years immediately preceding the sample periods. 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

¹⁰Paraná is a southern Brazilian state. It is not part of the Legal Amazon.

¹¹Local 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 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.

¹²Soybean, 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.

¹³PAM provides the data on annual municipal harvested area.

five weighted real prices. The first column of Table II 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.

The second variable of interest is an annual index of cattle prices, which is derived analogously to PPA_{itc} in Equation 6. 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 nature of the two policy turnings points discussed in Section 3, 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. Second, results from our conceptual framework, which indicate that conservation policies are binding when optimal farmland size exceeds that of the farmers’s landholding. If all farmers (and their respective decisions and landholdings) operating within a municipality are aggregated, the model’s reasoning can be extended to the municipal level – conservation policies should be binding, and thereby effective, in municipalities where land constraints are tight. In light of this, 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.

We explore two alternative proxy variables for the tightness of municipal land constraints, as suggested by our model’s empirical implications (see Section 4.3). The first proxy measures the area that is not legally available to farmers for production – in our model’s terminology, land beyond $\bar{T}$ – as a share of total municipal area. Essentially, this proxy captures how constrained farmers in a given municipality actually are. If the area they can legally deforest for production is small relative to total municipal area, land constraints are tight – $\bar{T}$ 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.

We use data from the 2006 Brazilian Agricultural Census to estimate the tightness of municipal land constraints in our sample.¹⁴ The proxy variable is defined as:

$$Tight_i = \frac{Area_i - Hydro_i - (Landholding_i - Unsuitable_i - LR_i - APP_i)}{Area_i} \quad (7)$$

where $Tight_i$ indicates how tight the land constraint is in municipality i ; $Area_i$ is the total area of municipality i ; $Hydro_i$ is the area covered by hydrographic features in municipality i ; $Landholding_i$ is the total area occupied by private rural establishments in municipality i ; $Unsuitable_i$ is the total area within private rural establishments in municipality i that is unsuitable for agricultural activity (namely degraded land, unviable land, and constructions); LR_i is the total area of legal reserves within private rural establishments in municipality i ; and APP_i is the total area of permanent protection within private rural establishments in municipality i . Note that while clearing forest areas for use in agricultural production is only legal within private landholdings, it is unfeasible in areas unsuitable for agricultural activity, and illegal in legal reserves and in areas of permanent protection. As these areas are all contained within private rural establishments, they must be deducted from the total area of landholdings to account for the restriction they impose upon expansion of agricultural land. Hence, $Tight_i$ measures the relative size of land that is legally available to farmers for use in agricultural production in municipality i – the larger the value of $Tight_i$, the smaller the relative size of legally available land, and, thus, the tighter the municipal land constraint.

The second proxy variable for the tightness of municipal land constraints suggested by our conceptual framework is $D_{i,2004}$, the normalized annual deforestation increment for municipality i in $t = 2004$. Recall that our model implies that farmers will respond to rising agricultural output prices by expanding farmland, and that sufficiently high prices ($p > \bar{P}_2$) will push optimal farmland beyond original landholdings ($\bar{T}$), 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 $\bar{T}$ at the time. Because this alternative proxy variable depends on conjunctural price fluctuations, which are potentially noisy and can

¹⁴Ideally, the proxy variable for tightness of municipal land constraint should be constructed using data collected before the sample period to ensure this data, and thereby the proxy variable constructed from it, have 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.

introduce measurement error, we do not use it in our main specifications, but rather in 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 composed of either fixed or slow-moving variables at the municipality level. The interaction of $Tight_i$ with the policy turning points thus results in policy variables which gain sharp time and cross-sectional exogenous variation within our panel of data at the municipality level. We argue that, 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.

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 equation

$$D_{it} = \alpha_i + \phi_t + M'_{it}\beta_1 + \beta_2 P_{i,t-1} + \beta_3(Tight_i * Post2004) + \beta_4(Tight_i * Post2008) + X'_{it}\beta_5 + \epsilon_{it} \quad (8)$$

where D_{it} is the normalized deforestation increment in municipality i between the 1st of August of $t - 1$ and the 31st of July of t . The first two terms on the right-hand side of model (8) 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 (8) 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 $\bar{T}$.

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 III 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 standard deviation increase of 1 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.

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 III use the culture-specific crop price indices defined in equation (6) 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 IV, 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, but no significant 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 given 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 standard deviation point of the deforestation increment. The 2008 policy turning point is associated with an impact of 0.7 standard deviation points.

In the following columns of Table IV, 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 of 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 both alternative proxy variables for $Tight_i$ and alternative 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 IV, 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:

$$\begin{aligned} \hat{D}_{it} = & \hat{\alpha}_i + \hat{\phi}_t + M'_{it}\hat{\beta}_1 + \hat{\beta}_2 P_{i,t-1} + \hat{\beta}_3 (Tight_i * Post2004) \\ & + \hat{\beta}_4 (Tight_i * Post2008) + X'_{it}\hat{\beta}_5 + I'_{it}\hat{\beta}_6 \end{aligned} \quad (9)$$

where $\hat{D}_{it}$ 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 $\hat{D}_{it}$ 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 $\hat{D}_{it}$ across all 380 sample municipalities and all sample years to calculate total predicted deforestation in the absence of these policies.

Column 1 of Table V shows the total observed deforestation trend for the 2002 through 2009 period. In column 2, we present the counterfactual trend for the hypothetical scenario described above. As seen in column 1, 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 119,200 square kilometers, as shown in column 2. Results therefore suggest that conservation policies avoided 62,100 square kilometers of deforestation, or 52.1% 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 2.3 billion tonnes of stored carbons dioxide, and is valued at USD 11.5 billion.¹⁵

Figure 6 plots the observed (column 1) and simulated (column 2) 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 10,200 square kilometers per year for 2005 through 2008, and at more than 20,000 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.

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, GDP per capita, and agricultural production. We follow our benchmark model (8), 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; (v) crop production per sowed hectare; and (vi) log of municipality herd of cattle.

Table VIII presents the results. In the first two columns we observe no significant impacts on population trends (column 1) or on overall GDP per capita (column 2). These results are qualitatively important since they suggest that there has not existed any important trade-off between conservation policies and local development in the Amazon context. We further examine this view by focusing on the agricultural sector in the remaining columns. In column 3 we find a negative relationship between sowed area and

¹⁵Estimations are based on conversion factors of 10,000 tC/km² (36,700 tCO₂/km²) and 5 USD/tCO₂, as established in DPCD/MMA (2011).

the 2004 policy turning point, which seems associated with a decline in the ratio of the sowed area to the municipality area size of 1.7 percentage points. On the other hand, column 4 shows that there is no significant correlation between the 2004 policy turning point and municipality crop production, though the point estimate is also negative. Despite these negative coefficients, in the following column we find a positive relationship between the 2004 turning point and crop productivity, significant at 10%. The coefficient associated with this impact (0.039) represents about 23% of the sample mean. In the last column we find no association between conservation policies and the size of municipality cattle herd. Finally, we observe no overall association between the 2008 policy turning point and the agricultural sector performance, though both sowed area and herd size coefficients report positive point estimates. 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 specification (8) 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 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.

8.1 The Timing of Price Variations and Deforestation

In Table VI, 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 III, columns 1 through 4. In column 1 of Table VI, we add future ($t + 1$) and past ($t - 2$) crop prices as regressors. As in Table III, 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.

In columns 2 through 4, we repeat the analysis for specific periods. As in Table III, 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 VII repeats the baseline specification found in column 2 of Table IV. In columns 2 and 3, we replace our baseline proxy variable for tightness with alternative variables.

In column 2, our baseline proxy is replaced with a dummy variable indicating those municipalities placed over the 75th percentile 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. Although noisy due to outliers and large municipalities, the results remain robust.

We also perform counterfactual simulations based on the specification of column 5, Table VII, where our baseline proxy for tightness is replaced by the variable $D_{i,2004}$. In this case, we find that effects are smaller but still sizeable.¹⁶ Counterfactual total deforestation is estimated at 84,100 square kilometers had the set of conservation policies introduced beginning in 2004 and 2008 not been adopted. This represents a total of 27,000 square kilometers of avoided deforestation, or 32.1% of the total deforestation that would have occurred from 2005 through 2009 in the absence of such policies in this alternative simulation. This is equivalent to an avoided loss of 991 million tonnes of stored carbon dioxide and is valued at USD 5.0 billion.¹⁷

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 62,100 square kilometers of deforestation in the 2005 through 2009 period. This represents approximately half of the forest area that would have been cleared had the policies not been introduced. This is equivalent to an avoided loss of 2.3 billion tonnes of stored carbon dioxide and is valued at USD 11.5 billion US. Analogous calculations for an alternative simulation confirm the sizeable impact of policies.

¹⁶The smaller effect can potentially be driven by measurement error in tightness, as $D_{i,2004}$ is a response to conjunctural price fluctuations.

¹⁷Estimations are based on conversion factors of 10,000 tC/km² (36,700 tCO₂/km²) and 5 USD/tCO₂, as established in DPCD/MMA (2011).

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.

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.

References

- Aadland, D. and Bailey, D. (2001). Short-Run Supply Responses in the U.S. Beef-Cattle Industry. *American Journal of Agricultural Economics*, 84(4):826–839.
- Andam, K. S., Ferraro, P. J., Pfaff, A., Sanchez-Azofeifa, G. A., and Robalino, J. A. (2008). Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of the National Academy of Sciences*, 105(42):16089–16094.
- Andersen, L. E. (1996). The causes of deforestation in the brazilian amazon. *The Journal of Environment & Development*, 5(3):309–328.
- Angelsen, A. and Kaimowitz, D. (1999). Rethinking the Causes of Deforestation: Lessons from Economic Models. *The World Bank Research Observer*, 14(1):73–98.
- Antle, J. M. and Heidebrink, G. (1995). Environment and development: Theory and international evidence. *Economic Development and Cultural Change*, 43:604–625.
- Araujo, C., Bonjean, C. A., Combes, J.-L., Motel, P. C., and Reis, E. J. (2009). Property Rights And Deforestation In The Brazilian Amazon. *Ecological Economics*, 68(8-9):2461–2468.
- Arcand, J.-L., Guillaumont, P., and Jeanneney, S. G. (2008). Deforestation and the real exchange rate. *Journal of Development Economics*, 86(2):242–262.
- Arima, E. Y., Simmons, C. S., Walker, R. T., and Cochrane, M. A. (2007). Fire in the Brazilian Amazon: A Spatially Explicit Model for Policy Impact Analysis. *Journal of Regional Science*, 47(3):541–567.

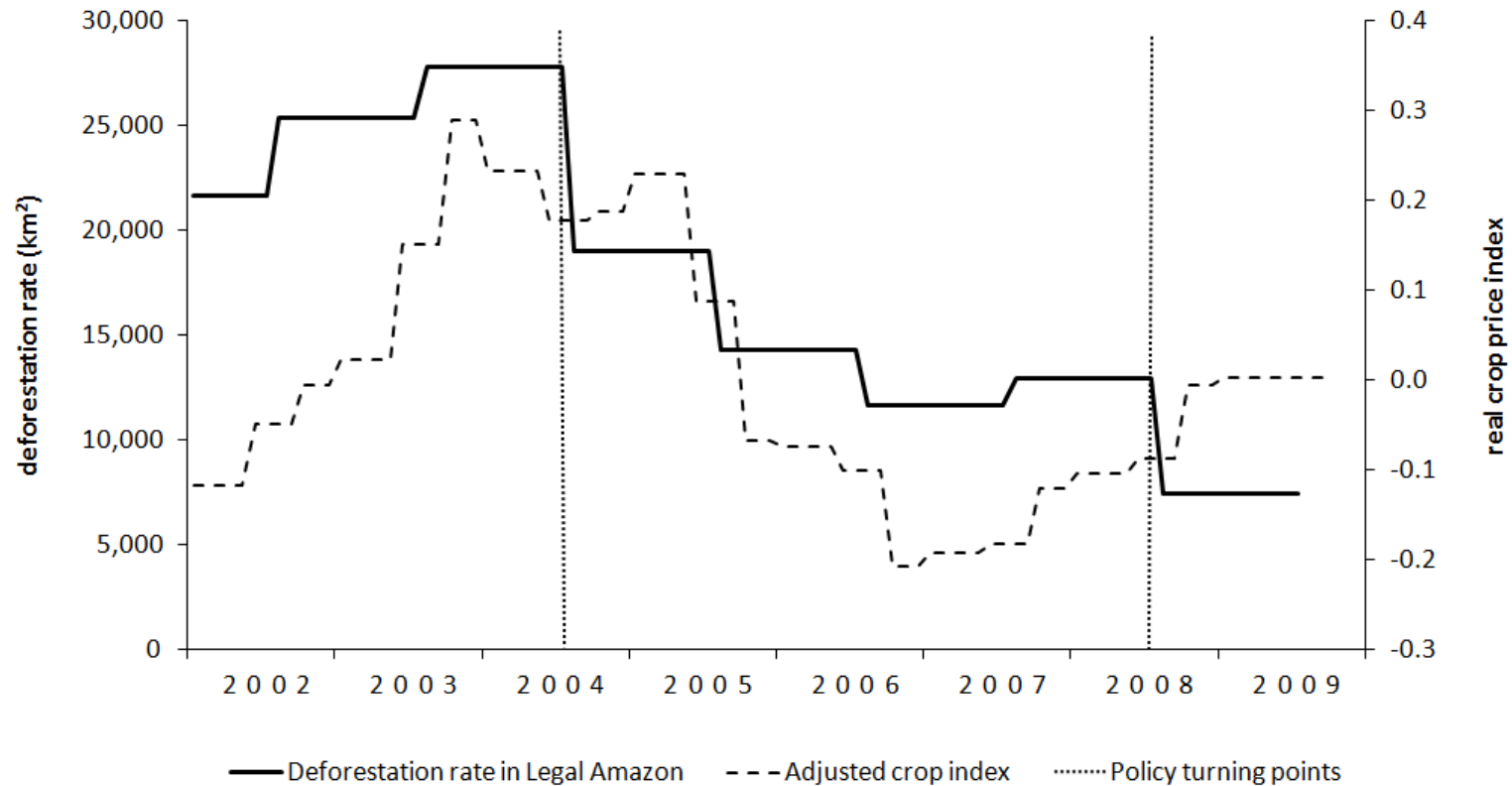
- Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C. S., Jansson, B., Levin, S., Maler, K., Perrings, C., and Pimentel, D. (1996). Economic growth, carrying capacity, and the environment. *Ecological Applications*, 6:13–15.
- Barbier, E. B. and Burgess, J. C. (1996). Economic analysis of deforestation in Mexico. *Environment and Development Economics*, 1(02).
- Barbier, E. B. and Burgess, J. C. (2001). The Economics of Tropical Deforestation. *Journal of Economic Surveys*, 15(3):413–433.
- Barreto, P., Pereira, R., and Arima, E. (2008). *A pecuária e o desmatamento na Amazônia na era das mudanças climáticas*. Instituto do Homem e Meio Ambiente da Amazônia.
- Burgess, R., Hansen, M., Olken, B. A., Potapov, P., and Sieber, S. (2012). The Political Economy of Deforestation in the Tropics. *The Quarterly Journal of Economics*, 127(4):1707–1754.
- Casa Civil (2004). Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal. Action plan, Casa Civil da Presidência da República, Brasília.
- Chomitz, K. and Thomas, T. (2003). Determinants of Land Use in Amazônia: A Fine-Scale Spatial Analysis. *American Journal of Agricultural Economics*, 85(4):1016–1028.
- Chomitz, K. M. and Gray, D. A. (1996). Roads, Land Use, and Deforestation: A Spatial Model Applied to Belize. *The World Bank Economic Review*, 10(3):487–512.
- Cropper, M. and Griffiths, C. (1994). The Interaction of Population Growth and Environmental Quality. *The American Economic Review*, 84(2):250–254. Papers and Proceedings of the Hundred and Sixth Annual Meeting of the American Economic Association.
- Cropper, M. L., Griffiths, C. W., and Mani, M. (1997). Roads, Population Pressures, and Deforestation in Thailand, 1976–89. World Bank Policy Research Working Paper No. 1726.
- Ewers, R. M., Laurance, W. F., and Souza Jr, C. M. (2008). Temporal Fluctuations In Amazonian Deforestation Rates. *Environmental Conservation*, 35(4):303–310.
- FAO (2006). Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management. Rome: Food and Agriculture Organization (FAO).
- Ferraz, C. (2001). Explaining Agriculture Expansion and Deforestation: Evidence from the Brazilian Amazon 1980/98.

- Foster, A. and Rosenzweig, M. (2003). Economic Growth and The Rise Of Forests. *The Quarterly Journal of Economics*, 118(2):601–637.
- Grossman, G. M. and Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics*, 110:353–377.
- Hargrave, J. and Kis-Katos, K. (2012). Economic Causes of Deforestation in the Brazilian Amazon: A Panel Data Analysis for 2000s. *Environmental and Resource Economics*.
- INPE (2012). Projeto prodes - monitoramento da floresta amazônica brasileira por satélite. Database, INPE.
- IPAM (2009). Evolução na Política para o Controle do Desmatamento na Amazônia Brasileira: O PPCDAm. *Clima e Floresta*, 15(15).
- IPCC (2007). *Climate Change 2007: Synthesis Report*. New York: Cambridge University Press.
- Jarvis, L. S. (1974). Cattle as Capital Goods and Ranchers as Portfolio Managers: An Application to the Argentine Cattle Sector. *Journal of Political Economy*, 82:489–520.
- Joppa, L. N. and Pfaff, A. (2011). Global protected area impacts. *Proceedings of the Royal Society B: Biological Sciences*, 278(1712):1633–1638.
- Maia, H., Hargrave, J., Gómez, J. H., and Röper, M. (2011). Avaliação do Plano de Ação para a Prevenção e Controle do Desmatamento da Amazônia Legal, 2007-2010. Technical report, Ipea, GIZ and Cepal.
- Mendonça, M. J. C., Loureiro, P. R. A., and Sachsida, A. (2012). The Dynamics of Land-Use in Brazilian Amazon. *Ecological Economics*, 84:23–36.
- Ministério de Ciência e Tecnologia (2010). *Inventário Brasileiro de Emissões Antrópicas por Fontes e Remoções por Sumidouros de Gases de Efeito Estufa não Controlados pelo Protocolo de Montreal*. Brasília: Ministério de Ciência e Tecnologia.
- MMA (2011). Ratificação da Estimativa de Redução de Emissões de CO₂ pelo Desflorestamento na Amazônia Legal com Base no PRODES 2010. Technical report, Ministério do Meio Ambiente.
- Nelson, A. and Chomitz, K. M. (2011). Effectiveness of Strict vs. Multiple Use Protected Areas in Reducing Tropical Forest Fires: A Global Analysis Using Matching Methods. *PLoS ONE*, 6(8):e22722.

- Nolte, C., Agrawal, A., Silvius, K. M., and Soares-Filho, B. S. (2013). Governance regime and location influence avoided deforestation success of protected areas in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*.
- Panayotou, T. (1995). Environmental degradation at different stages of economic development. In Ahmed, I. and Doeleman, J. A., editors, *Beyond Rio: The The Environmenatl Crisis and Sustainable livelihoods in the Third World*, pages 13–36. London: Macmillan Press.
- Panayotou, T. and Sungsuwan, S. (1994). *An Econometric Analysis of the Causes of Tropical Deforestation: The Case of Northeast Thailand*, chapter In: The Causes of Tropical Deforestation: The Economic and Statistical Analysis of Factors Giving Rise to the Loss of the Tropical Forests, pages 192–210. University College of London Press.
- Pfaff, A. (1999). What Drives Deforestation in the Brazilian Amazon? Evidence from Satellite and Socioeconomic Data. *Journal of Environmental Economics and Management*, 37(1):26–43.
- Pfaff, A., Robalino, J., and Herrera, D. (2011). Decentralization Given Environment-Development Tradeoffs: Federal Versus State Conservation and Impacts on Amazon Deforestation. In *Association of Environmental and Resource Economists (AERE), Summer Conference*, Seattle.
- Pfaff, A., Robalino, J., Walker, R., Aldrich, S., Caldas, M., Reis, E., Perz, S., Bohrer, C., Arima, E., Laurance, W., and et al. (2007). Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. *Journal of Regional Science*, 47(1):109–123.
- Pfaff, A., Sills, E. O., Amacher, G. S., Coren, M. J., Lawlor, K., and Streck, C. (2010). Policy Impacts on Deforestation: Lessons Learned from Past Experiences to Inform New Initiatives. Technical report, Nicholas Institute for Environmental Policy Solutions at Duke University.
- Reis, E. and Guzmán, R. (1994). An Econometric Model of Amazon Deforestation. In *K. Brown and D. Pearce, eds. The Causes of Tropical Deforestation*. London: UCL Press, pages 172–191.
- Reis, E. and Margulis, S. (1991). Options for Slowing Amazon Jungle Clearing. In *R. Dornbusch and J.M. Poterba, eds. Global Warming: Economic Policy Responses*. Cambridge, MA: MIT Press, pages 335–375.
- Rosen, S., Murphy, K. M., and Scheinkman, J. A. (1994). Cattle Cycles. *Journal of Political Economy*, 102(3):468–492.

- Sims, K. R. (2010). Conservation And Development: Evidence From Thai Protected Areas. *Journal of Environmental Economics and Management*, 60(2):94–114.
- Soares-Filho, B., Moutinho, P., Nepstad, D., Bowman, M., Rodrigues, H., Anderson, A., Garcia, R., Dietzsch, L., Merry, F., Hissa, L., Silvestrini, R., and Maretti, C. (2010). Role of Brazilian Amazon Protected Areas in Climate Change Mitigation. *Proceedings of the National Academy of Sciences*, 107(24):10821–10826.
- Weinhold, D. and Reis, E. (2008). Transportation costs and the spatial distribution of land use in the Brazilian Amazon. *Global Environmental Change*, 18(1):54–68.

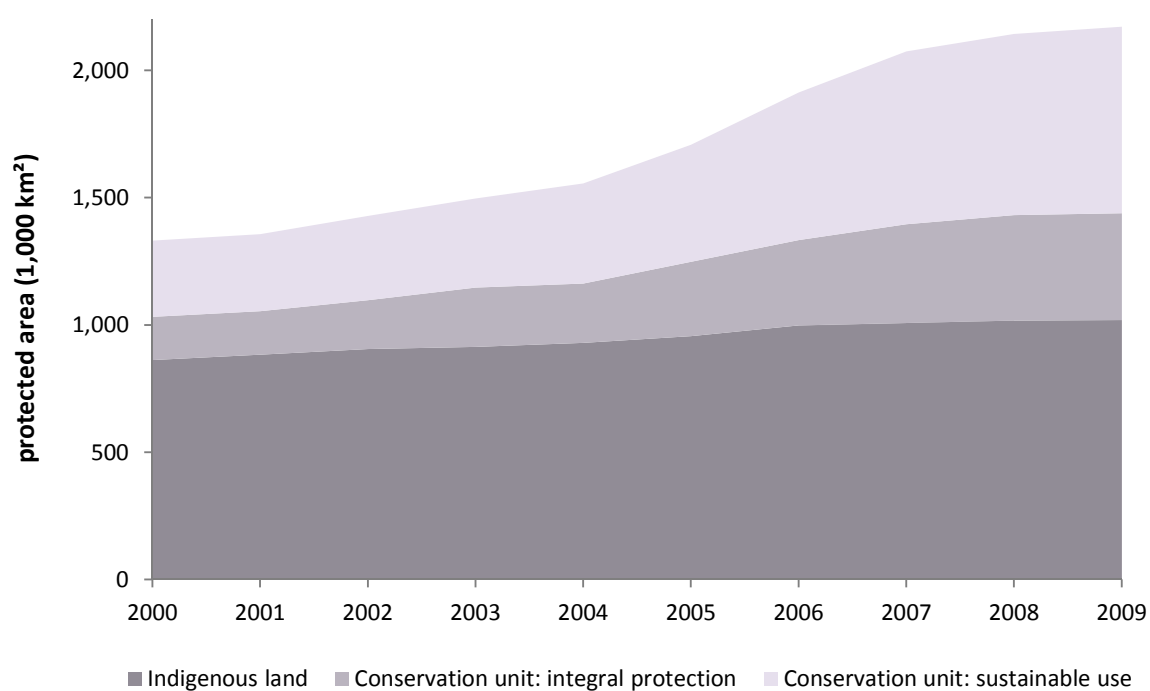
Figure 1: Amazon Deforestation Rate and Agricultural Price Trends, 2002-2009



Notes: 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).

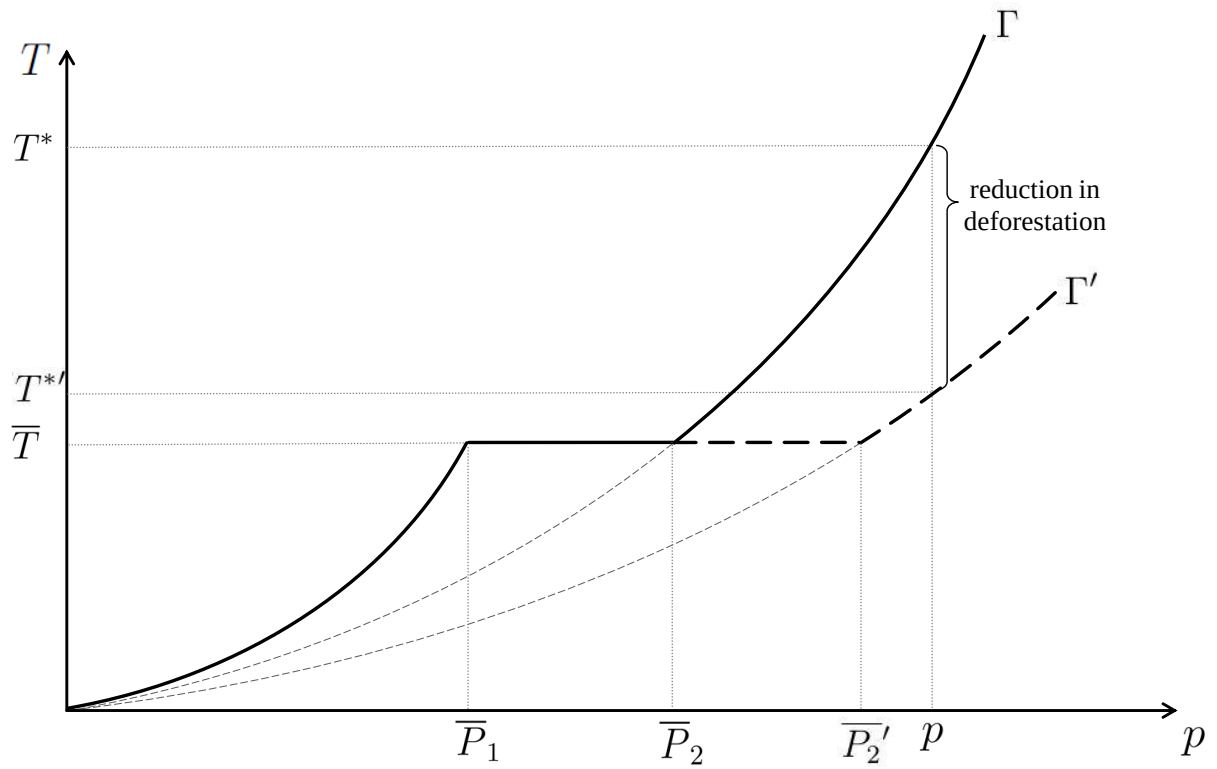
Source: Authors' elaboration based on data from PRODES/INPE and SEAB-PR.

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



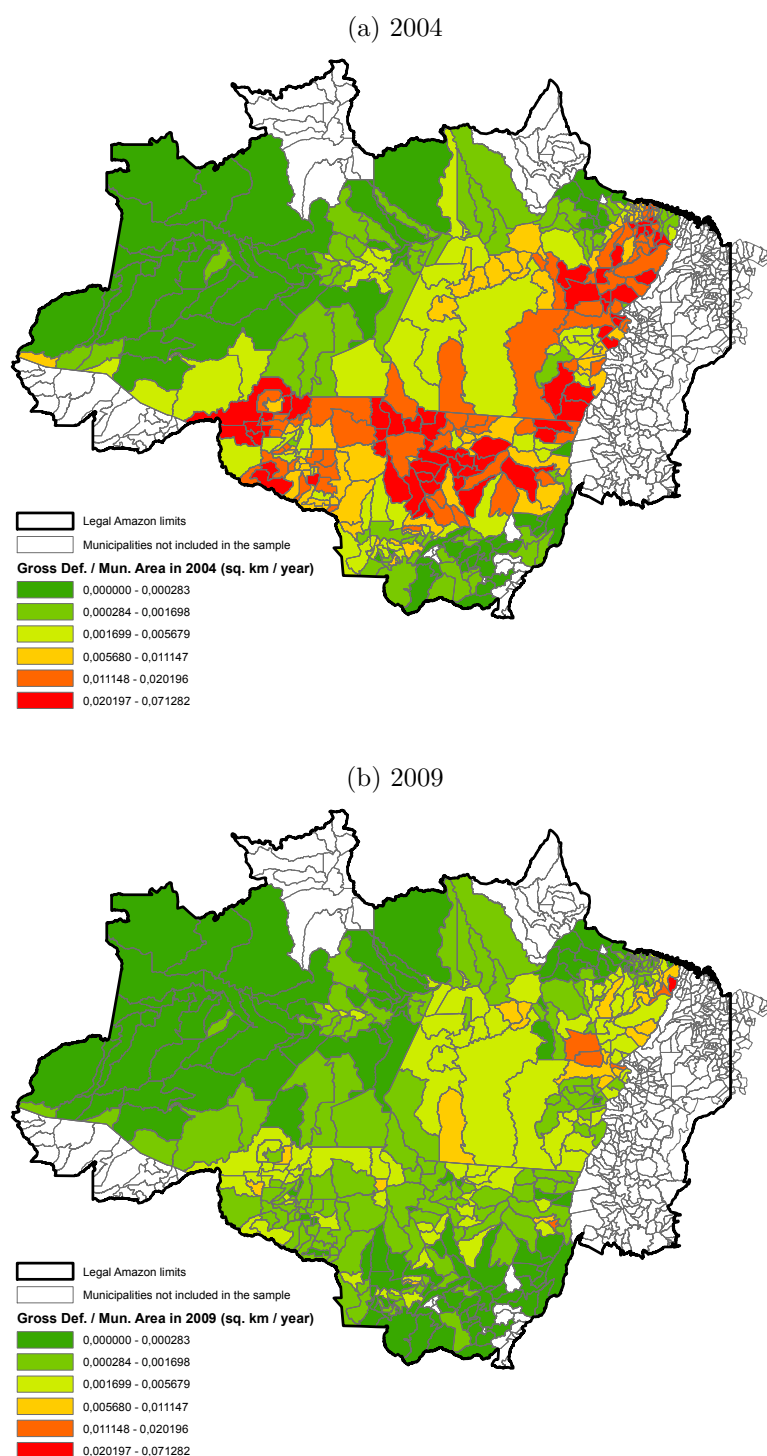
Source: Authors' elaboration based on data from the National Registry of Conservation Units (CNUC/MMA) and the National Indigenous Peoples Foundation (FUNAI).

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



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

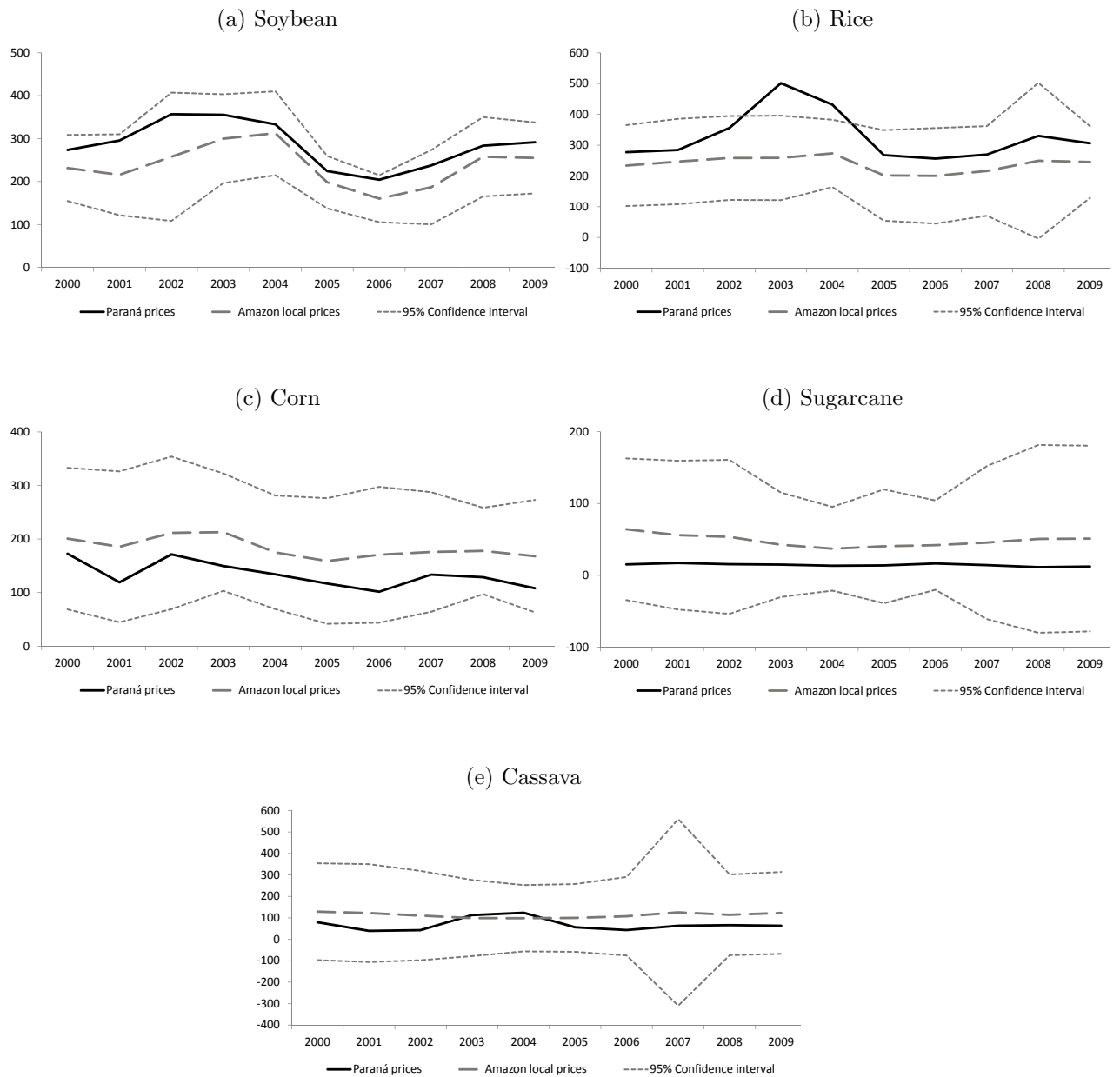
Figure 4: Gross Deforestation Increment per Municipal Area



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

Source: Authors' elaboration based on data from PRODES/INPE.

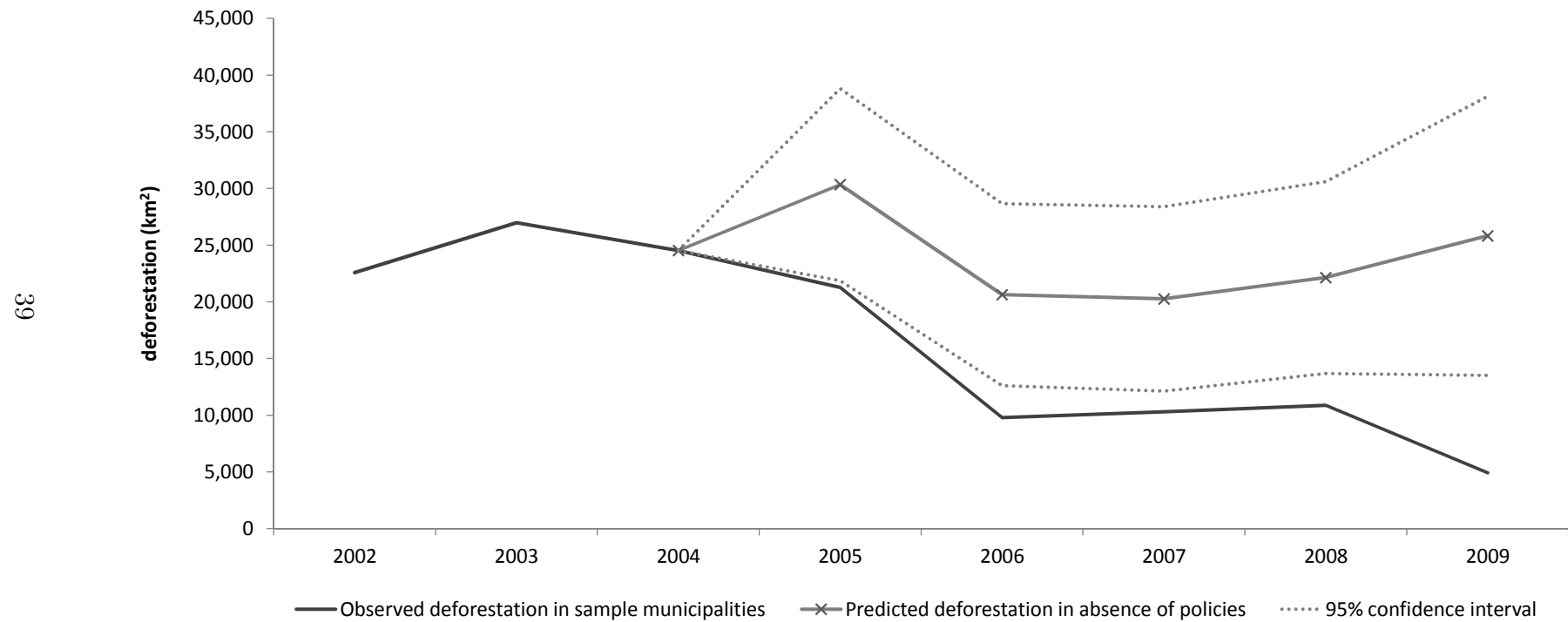
Figure 5: Paraná Price Series and Average Amazon Prices, 2000-2009



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

Source: Authors' elaboration based on data from SEAB-PR and PAM.

Figure 6: Counterfactual Simulation - What Would Have Happened in the Absence of the Policy Change?



Notes: Authors' elaboration based on data from Table V. Counterfactual simulations based on model (9).

Table I: Comparative Statics - 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	–

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

Component of PCA	Weights of 1 st	Sown Area as Share of:					
		Total Municipality Area			Total Municipality Sown Area		
		2002	2009	Difference	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: Agricultural price data originally from SEAB-PR, and municipality agricultural production data originally from PAM. Sample includes 380 municipalities located in the states of Amazonas, Mato Grosso, Pará, and Rondônia.

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

	Annual Normalized Deforestation Increment (From August t-1 Through July t)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Crops Price Index (t-1)	0.229 (0.069)***								
Crops Price Index (Jan-May, t-1)		0.196 (0.062)***							
Crops Price Index (June-Sept, t-1)			0.223 (0.073)***						
Crops 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 (current: 1 st sem, t)	-0.021 (0.007)***	-0.020 (0.007)***	-0.021 (0.007)***	-0.023 (0.007)***	-0.023 (0.007)***	-0.023 (0.007)***	-0.023 (0.007)***	-0.019 (0.007)***	-0.022 (0.007)***
Cattle Price Index (lagged: Jan-Dec, t-1)	0.010 (0.006)*	0.010 (0.006)*	0.010 (0.006)*	0.013 (0.006)**	0.014 (0.006)**	0.012 (0.006)**	0.013 (0.006)**	0.008 (0.006)	0.013 (0.006)**
Observations	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040
Number of Municipalities	380	380	380	380	380	380	380	380	380
Year and Municipality Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls and Municipality 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 IV: The Effect of Conservation Policies on Deforestation

	Annual Normalized Deforestation Increment				
	(1)	(2)	(3)	(4)	(5)
Tight*Post2004	-0.527 (0.181)***	-1.451 (0.384)***	-1.391 (0.425)***	-1.408 (0.397)***	-1.439 (0.432)***
Tight*Post2008	0.231 (0.171)	-1.056 (0.308)***	-1.029 (0.307)***	-1.179 (0.309)***	-1.188 (0.315)***
Crops Price Index	0.245 (0.052)***	0.268 (0.076)***	0.060 (0.247)	0.075 (0.273)	0.076 (0.269)
Cattle Price Index (current)	-0.025 (0.006)***	0.003 (0.010)	0.001 (0.010)	0.001 (0.010)	0.001 (0.010)
Cattle Price Index (lagged)	0.033 (0.006)***	-0.012 (0.009)	-0.010 (0.009)	-0.010 (0.009)	-0.010 (0.009)
Tight*Crops Price Index			0.447 (0.469)	0.495 (0.521)	0.491 (0.517)
Crops Price Index*Post2004			0.009 (0.150)		-0.003 (0.148)
Crops Price Index*Post2008				-0.046 (0.118)	-0.047 (0.110)
Tight*Crops Price Index*Post2004			-0.012 (0.299)		-0.020 (0.300)
Tight*Crops Price Index*Post2008				-0.052 (0.227)	-0.057 (0.219)
Observations	3,040	3,040	3,040	3,040	3,040
Number of Municipalities	380	380	380	380	380
Year and Municipality Fixed Effects	Yes	Yes	Yes	Yes	Yes
Controls and Municipality 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 V: Counterfactual Simulations - Observed and Predicted Deforestation (in km^2)

Year	Observed Deforestation in Sample Municipalities	Predicted Deforestation if Post2004=0 & Post2008=0
2002	22,574	22,574
2003	26,980	26,980
2004	24,526	24,526
2005	21,273	30,335
2006	9,786	20,629
2007	10,304	20,253
2008	10,872	22,140
2009	4,909	25,823
Total 2005-2009 (in km^2)	57,144	119,182
Avoided Deforestation 2005-2009 (in km^2)	-	62,038
Avoided Deforestation 2005-2009 (in % of Deforestation if Post2004=0 & Post2008=0)		52,1%

Notes: Counterfactual simulations based on model (9). Simulation 1 is based on the specification presented in column 4 of Table IV, which includes the full set of fixed effects, specific time trends, and price interactions. Simulation 2 uses specification in column 6 of Table IV instead. Both specifications are 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 VI: The Timing of Price Variation and Deforestation Rates: Placebo Regressions

	Annual Normalized Deforestation Increment			
	(1)	(2)	(3)	(4)
Crops Price Index (t-1)	0.390 (0.181)**			
Crops Price Index (t+1)	-0.027 (0.215)			
Crops Price Index (t-2)	0.066 (0.188)			
Crops Price Index (Jan-May, t-1)		0.228 (0.125)*		
Crops Price Index (Jan-May, t+1)		0.077 (0.164)		
Crops Price Index (Jan-May, t-2)		-0.006 (0.136)		
Crops Price Index (June-Sept, t-1)			0.434 (0.161)***	
Crops Price Index (June-Sept, t+1)			0.045 (0.156)	
Crops Price Index (June-Sept, t-2)			0.188 (0.158)	
Crops Price Index (Oct-Dec, t-1)				0.135 (0.094)
Crops Price Index (Oct-Dec, t+1)				-0.139 (0.159)
Crops Price Index (Oct-Dec, t-2)				0.101 (0.117)
Cattle Price Index (current: 1st sem, t)	-0.112 (0.022)***	-0.114 (0.022)***	-0.109 (0.022)***	-0.113 (0.022)***
Cattle Price Index (lagged: Jan-Dec, t-1)	0.180 (0.040)***	0.185 (0.039)***	0.175 (0.039)***	0.183 (0.040)***
Observations	2,280	2,280	2,280	2,280
Number of Municipalities	380	380	380	380
Year and Municipality Fixed Effects	Yes	Yes	Yes	Yes
Controls and Municipality 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 VII: Alternative Dependent Variable and Proxy Variables for Tightness - Robustness Checks

	Normalized Deforestation Increment					Deforestation Increment (in km^2)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Tight*Post2004	-1.451 (0.384)***	-0.746 (0.186)***	-0.748 (0.065)***	-0.739 (0.199)***	-0.740 (0.069)***	-37.784 (14.124)***	-27.115 (5.920)***	-16.179 (3.745)***
Tight*Post2008	-1.056 (0.308)***	-0.451 (0.136)***	-0.516 (0.057)***	-0.536 (0.146)***	-0.533 (0.058)***	-36.351 (9.987)***	-19.414 (4.406)***	-14.180 (2.364)***
Crops Price Index	0.268 (0.076)***	0.268 (0.075)***	0.208 (0.067)***	0.243 (0.087)***	-0.073 (0.135)	-50.260 (12.161)***	-4.763 (2.984)	-16.804 (4.679)***
Cattle Price Index (current)	0.003 (0.010)	-0.002 (0.009)	-0.019 (0.008)**	-0.003 (0.009)	-0.017 (0.008)**	0.274 (0.275)	0.433 (0.248)*	-0.128 (0.206)
Cattle Price Index (lagged)	-0.012 (0.009)	-0.005 (0.008)	0.008 (0.006)	-0.004 (0.008)	0.009 (0.006)	-0.307 (0.277)	-0.508 (0.233)**	-0.060 (0.183)
Tight*Crops Price Index				0.246 (0.158)	0.277 (0.114)**	109.641 (27.952)***	23.170 (10.346)**	14.005 (3.956)***
Crops Price Index*Post2004				-0.031 (0.053)	0.177 (0.107)*	-2.977 (7.388)	-3.993 (0.908)***	-0.909 (1.462)
Crops Price Index*Post2008				-0.067 (0.032)**	0.029 (0.044)	5.951 (4.966)	1.172 (1.487)	5.877 (1.740)***
Tight*Crops Price Index*Post2004				0.057 (0.108)	-0.072 (0.063)	-0.045 (16.842)	1.292 (3.855)	0.885 (0.898)
Tight*Crops Price Index*Post2008				-0.012 (0.067)	-0.018 (0.026)	-10.394 (10.068)	-0.294 (2.934)	-2.042 (1.055)*
Observations	3,040	3,040	3,040	3,040	3,040	3,040	3,040	3,040
Number of Municipalities	380	380	380	380	380	380	380	380
Year and Municipality Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls and Municipality Time Trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Robustness	Tight = Baseline	Tight = Dummy: Baseline> pc 75%	Tight = Deforestation in 2004	Tight = Dummy: Baseline> pc 75%	Tight = Deforestation in 2004	Tight = Baseline	Tight = Dummy: Baseline> pc 75%	Tight = Deforestation in 2004

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 VIII: Impacts on Population, GDP, and Agricultural Production

	Ln(Population)	Ln(GDP Per Capita)	Sowed Area / Municipality Area	Crops Production (1,000 Tonnes)	Productivity = Crops Production (1000 tonnes) / Sowed Area (ha)	Ln(Cattle)
	(1)	(2)	(3)	(4)	(5)	(6)
Tight*Post2004	-0.011 (0.028)	0.053 (0.055)	-0.017 (0.008)**	-9.269 (14.846)	0.039 (0.023)*	-0.037 (0.071)
Tight*Post2008	-0.004 (0.013)	0.061 (0.043)	0.007 (0.006)	-12.345 (9.025)	-0.004 (0.021)	0.125 (0.084)
Crops Price Index	-0.001 (0.005)	0.122 (0.025)***	0.010 (0.006)	21.743 (6.851)***	0.001 (0.003)	-0.001 (0.021)
Cattle Price Index (current)	0.002 (0.002)	-0.004 (0.002)**	0.000 (0.000)	0.110 (0.349)	0.001 (0.001)**	-0.002 (0.003)
Cattle Price Index (lagged)	0.000 (0.001)	-0.000 (0.002)	0.000 (0.000)	-0.527 (0.358)	0.000 (0.001)	0.006 (0.003)**
Mean of Dependent Variable	9.79	1.22	0.03	74.65	0.23	10.74
Coefficient for 2004 / Mean	-0.1%	4.3%	-57%	-12%	17%	0%
Coefficient for 2008 / Mean	0.0%	5.0%	23%	-17%	-2%	1%
Observations	3,040	3,040	3,040	3,040	3,040	3,024
Number of Municipalities	380	380	380	380	380	380
Year and Municipality Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Controls and Municipality Time Trends	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 in column 1 is the log of the municipality population (IBGE), while in column 2 is the log of the municipality GDP per capita (IBGE/Ipeadata). In the remainder columns we use data originally from PAM to build the outcome variables. 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.