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Deforestation Slowdown in the Legal Amazon: Prices or Policies?

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1 Introduction

Deforestation and biomass decay have accounted for approximately 17% of global greenhouse gas emissions (IPCC (2007)). This fact raises concerns about the extent of forest clearings in the Brazilian Amazon, the planet's largest rainforest tract. The region has long been the world's most active agricultural frontier in terms of forest loss and CO₂ emissions (FAO (2006), Morton et al., Santilli et al. (2005)). In Brazil, the conversion of forest areas in the Amazon biome has contributed nearly half of the country's total net CO₂ emissions (Ministério de Ciência e Tecnologia (2010)).

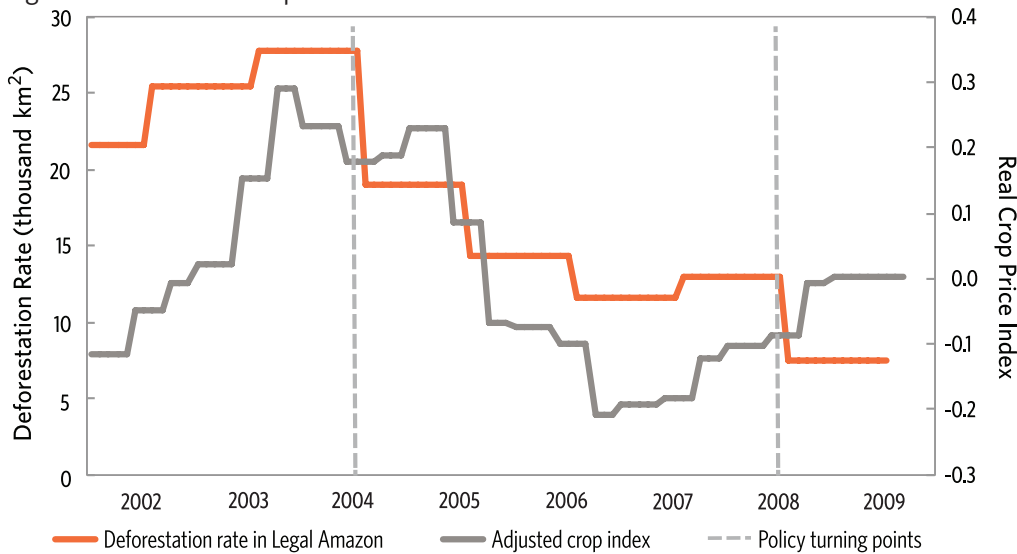
Nonetheless, the pace of forest clearings in the Brazilian Amazon slowed down substantially beginning in the mid-2000s. After gradually increasing to over 27,000 square kilometers in 2004, the deforestation rate in the Legal Amazon decreased almost continuously over the following years to about 7,000 square kilometers in 2009 (PRODES/INPE (2011)).¹ Although crucial from a policy perspective, empirical knowledge about the causal mechanisms behind the Legal Amazon deforestation slowdown is still scant.

Two alternative explanations stand out. On the one hand, as seen in Figure 1, the annual deforestation rate was highly correlated with variations in agricultural output prices, particularly in the first half of the decade. Market conditions may thus have contributed to the inhibiting of forest clearing for the expansion of farmland. On the other hand, conservation policies aimed at controlling and preventing deforestation in the Amazon underwent significant revisions during the 2000s, marked by two relevant turning points. First, the launch of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (*Plano de Ação para a Prevenção e o Controle do Desmatamento na Amazônia Legal*, PPCDAm) in 2004 integrated actions across different government institutions and introduced innovative procedures for monitoring, environmental control, and territorial management (Ipea et al. (2011), IPAM (2009)). Second, as novel policy measures were implemented beginning in 2008, the targeting of municipalities with critical rates of deforestation became operationally viable and rural credit became conditional upon proof of the borrower's compliance with environmental regulations. Figure 1 shows that the adoption of conservation policies following these turning points coincide with sharp subsequent decreases in the recorded rate of deforestation.

In this paper, we investigate the extent to which conservation policies have contributed to the recent deforestation slowdown in the Legal Amazon. The challenge is twofold. First, we need to disentangle the role of policies from potentially important price effects on deforestation. Second, we need to explore cross-sectional variation

¹ The Legal Amazon 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.

Figure 1: Deforestation and price trends



in our empirical setting in order to identify the effect of policies. Otherwise, we are not able to separate the effect of policies from other contemporaneous effects. As a starting point, we consider a conceptual framework in which a farmer decides whether or not to expand farmland beyond his landholding and thereby clear areas of forest, given a set of parameters regarding expected prices, policies, and technology. This framework suggests that conservation policies should be binding whenever the farmer faces a tight land constraint, that is, whenever optimal farmland size given prices and technology is larger than the farmer's landholding. The tightness of the land constraint is influenced by land endowment and agricultural output prices.

Our conceptual framework has two main implications that guide our empirical analysis. First, it suggests that we should control for agricultural prices in order to evaluate the impact of conservation policies. Second, it indicates that the farmer's response to policy stringency should depend on the tightness of the land constraints. This introduces cross-sectional variation in response to policy among different municipalities. Although not directly observed, the tightness of land constraints at the local level can be proxied by observed variables.

We apply this framework to evaluate the effectiveness of conservation policies introduced beginning in 2004 and 2008, considering a sample of municipalities from selected Legal Amazon states in the 2002 through 2009 period. Our dependent variable is the normalized deforestation increment for each municipality and year, constructed from satellite-based images that are processed by the National Institute of Spatial Research (*Instituto Nacional de Pesquisas Espaciais*, INPE).

We first analyze the effects of crop and cattle prices on deforestation. For crops, we use principal component analysis to build an annual local index of crop prices

that captures most of the joint variation in crop price series. For cattle, we consider prices for contemporaneous and lagged periods in order to account for potential cattle ranching cycles. Exogenous cross-sectional variation in price indices is obtained using agricultural prices from a southern Brazilian state weighted by the relative importance of different agricultural products at the local level. We find that deforestation is sensitive to crop and cattle prices, even after controlling for year and municipality fixed effects. This relationship also holds for specific crop indices. Results suggest that crop and cattle prices have different dynamic relationships with deforestation.

Given that prices are closely related to deforestation, as implied by both our conceptual framework and the empirical evidence, we then perform policy evaluation controlling for as much of the price effects as we can. In addition to the price index and the municipality and year fixed effects, we consider a set of municipality-specific time trends to account for other sources of price variation. The sets of conservation policies are represented by two dummy variables one for each of the 2004 and 2008 turning points and their interaction with a measure of the tightness of land constraints in each municipality. Our model, which implies that policies are expected to be more effective in areas with tighter land constraints, motivates the use of the interaction terms. Our baseline proxy for the tightness of the land constraint is a measure of the share of land unavailable for agriculture relative to the total area of each municipality (areas of public forest, legal reserve and protected areas, degraded land, hydrographic features, etc). This proxy is built from 2006 Agricultural Census data.

The empirical results indicate that the conservation policies associated with the two turning points were effective at curbing deforestation rates in Brazil. Observed deforestation in sample municipalities totaled 57,100 square kilometers in the states of Pará, Mato Grosso, Rondônia, and Amazonas for the 2005 through 2009 period. In counterfactual simulations we estimate that, had the set of conservation policies implemented beginning in 2004 and 2008 not been introduced, this total would have instead equaled 119,200 square kilometers. Our results therefore suggest that these conservation policies avoided 62,100 square kilometers of deforestation, or 52.1% of the total deforestation that would have occurred in the 2005 through 2009 period if policies had not been adopted. Using the conversion factors of 10,000 tons of C per square kilometer and 5 US dollars per ton of CO₂ mentioned in MMA (2011), this avoided deforestation is equivalent to an avoided loss of 621 million tons of stored C, or 2.3 billion tons of stored CO₂, which is valued at 11.5 billion US dollars.

This paper contributes to the literature on the determinants of deforestation in two ways. First, it performs an empirical analysis of the causal effects of agricultural output prices on deforestation. Although there is evidence supporting the assertion

that higher prices for agricultural products stimulate forest clearing (Angelsen and Kaimowitz (1999), Barbier and Burgess (1996), Panayotou and Sungsuwan (1994)), recent studies have found mixed results regarding the significance and even the direction of the correlation between output prices and deforestation in the Amazon region (Hargrave and Kis-Katos (2010), Araujo et al. (2009), Prates (2008), Ferraz (2001)). In fact, the lack of reliable microeconomic data and exogenous variation in output prices at the local level has limited the identification of output price effects (Angelsen and Kaimowitz (1999), Arcand et al. (2008)). In this paper, we explore exogenous variation in price indices obtained with the use of agricultural prices from a southern Brazilian state weighted by the relative importance of different agricultural products at the local level just before the period of analysis. In robustness checks, we use placebo regressions to further test our main results on prices.

Second, our core analysis evaluates the role of conservation policies in the Legal Amazon deforestation slowdown. Much of the literature on the underlying causes of deforestation has focused on major economic drivers of forest clearing, such as population pressures, economic growth, technological change, and macroeconomic trends (Angelsen and Kaimowitz (1999), Barbier and Burgess (2001)). Although potentially crucial to shape economic incentives behind farmers' land use decisions, changes to environmental and land use regulation have been relatively less studied in impact evaluations at the micro-level. Sources of exogenous variation in policy adoption across localities are often rare, while longitudinal data is usually restricted by quality concerns or time frame length. Within this context, many approaches have a tendency to be only descriptive or ad hoc. Recent attempts to evaluate conservation policies have focused on the impact of specific policy interventions, for which Geographic Information System (GIS) data is available, such as the designation of protected areas (Pfaff et al. (2011), Soares-Filho et al., Sims (2010)). In this paper, we explore local heterogeneity both conceptually and empirically to gain cross-sectional variation in policy stringency. This strategy enables us to advance with the evaluation of major policy interventions in the Legal Amazon region, and to test whether conservation policies played a relevant role in one of the greatest declines in deforestation rates recently experienced by a developing country.

This paper is organized as follows: Section 2 provides the policy background for the analysis; Section 3 introduces and develops the conceptual framework; Section 4 describes the data set and the main variables; Section 5 details our empirical strategy; Section 6 presents and discusses the results; Section 7 performs robustness checks; and Section 8 concludes.

2 Institutional Context

To better understand how conservation policies might have influenced deforestation in the Legal Amazon, this section presents a description of key changes to Brazilian environmental legislation during the period of interest. Throughout the last decade, the Brazilian Federal Government and the Ministry of the Environment (*Ministério do Meio Ambiente*, MMA) sought to inhibit forest clearings and promote forest conservation by directing their attention towards three main policy efforts: the strengthening of command and control strategies; the extensive expansion of protected territory; and the adoption of conditional credit policies. Although the pursuit of these efforts led to intense reformulation of conservation policies in the 2000s, two years stand out as important turning points within the country's institutional context: 2004 and 2008.

2.1 PPCDAm, 2004

The first turning point occurs with the launch of the PPCDAm in 2004. Its foundations date back to July 2003, when the Federal Government approved the creation of the Permanent Group of Interministerial Work (Grupo Permanente de Trabalho Interministerial, GPTI). Comprised of the heads of thirteen key Ministries and led by the Chief of Staff, the group's goal was to propose and coordinate actions aimed at reducing deforestation in the Legal Amazon (Casa Civil (2004)).² In March 2004, the GPTI 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 PPCDAm's plan of action focused on three main areas: (i) territorial management and land use, with particular attention to be given to land tenure disputes; (ii) command and control, as a means of improving monitoring, licensing and enforcement; and (iii) promotion of sustainable practices, including a revision of economic incentives for sustainable agriculture and forest management, better use of already-cleared lands, and development of sustainable transportation and energy infrastructure (Casa Civil (2004), May et al. (2011)).

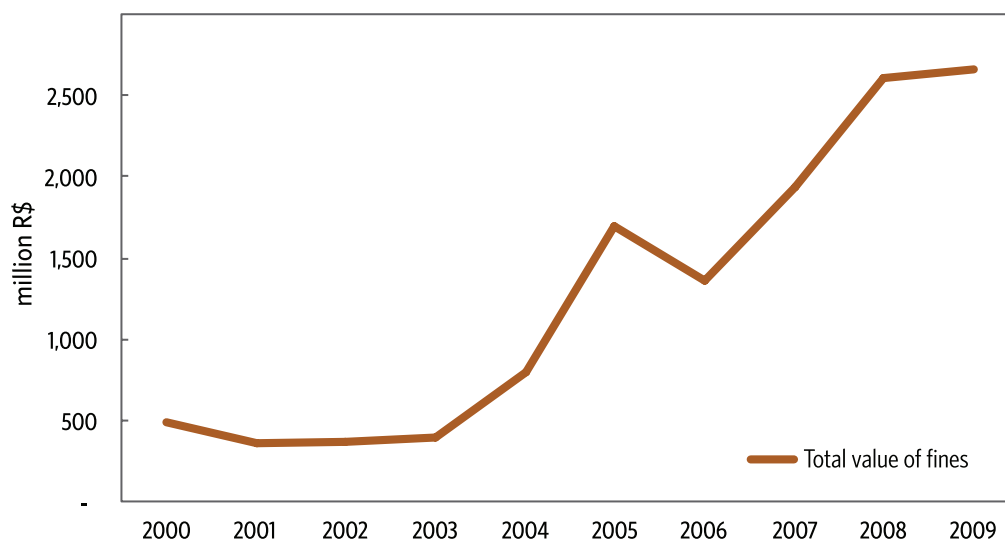
Several changes that occurred within the Brazilian environmental policy context since the launch of the PPCDAm fit into the plan's framework. Mutual cooperation between different levels and agencies of government provided support for the practice of stricter monitoring in the Legal Amazon.³ Remote sensing-based monitoring

² The Chief of Staff of the Presidency of the Republic is the highest-ranking member of the Executive Office of Brazil.

³ The July 2004 Interministerial Ordinance MMA-MD 702, for example, established the grounds for collaboration between the MMA and the Ministry of Defence.

capacity in the Legal Amazon also improved significantly after the creation, in 2004, of INPE's Real-Time System for Detection of Deforestation (*Sistema de Detecção de Desmatamento em Tempo Real*, DETER) and of the Center for Environmental Monitoring (*Centro de Monitoramento Ambiental*, CEMAM) at the Brazilian Environment and Renewable Natural Resources Institute (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis*, Ibama). Collaboration between INPE and CEMAM enabled the georeferenced imagery on changes to forest cover generated by DETER in 15-day intervals to be prepared and distributed in the form of georeferenced digital maps by CEMAM. These maps contain information on critical areas and serve as important tools in the targeting of law enforcement activities (May et al. (2011)). Prior to the activation of DETER in 2004, surveillance in the Legal Amazon relied strictly on denouncements of threatened areas. With the adoption of the new remote sensing system, however, Ibama was given speedier access to recent georeferenced data and was thus able to identify, monitor, and more quickly act within areas in need of monitoring. Additionally, in 2005, Ibama launched a program aimed at improving the qualification and thereby the image of its environmental monitoring personnel. This effort led to an increase not only in the number of Ibama supervisors, but also in their quality (interview with MMA personnel). Figure 2 shows that the value of fines issued by Ibama in Legal Amazon states significantly increased in the second half of the 2000s. Such pattern is indicative of more active environmental monitoring.

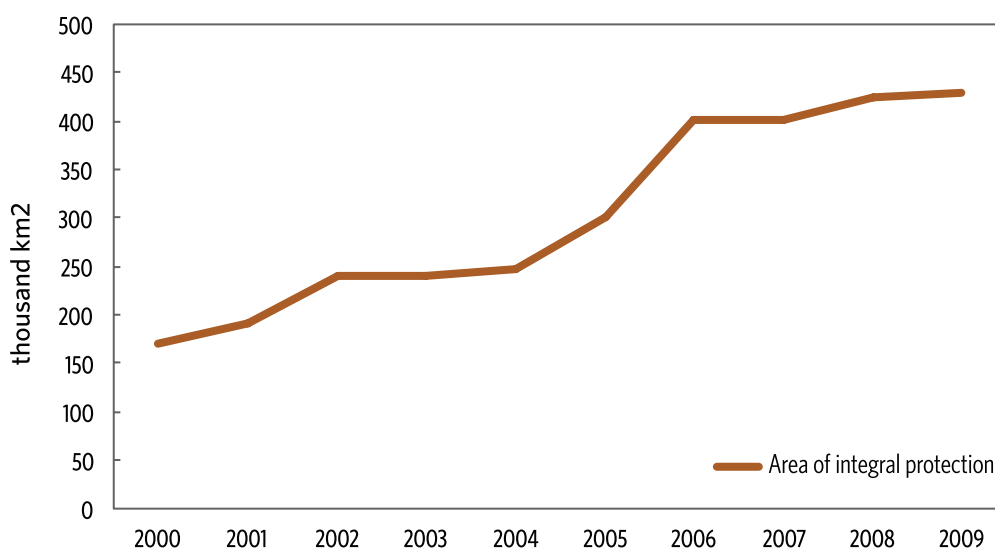
Figure 2: Total value of fines issued by Ibama in legal Amazon states



Notes: Authors' elaboration based on data from Ibama/MMA. Real values for 2009 calculated using the annual National Consumer Price Index (Índice Nacional de Preços ao Consumidor Amplo, IPCA/IBGE).

Parallel to the PPCDAm's command and control efforts, the creation of protected areas gained momentum in the mid-2000s. Although the National System of Nature's Conservation Units (*Sistema Nacional de Unidades de Conservação da Natureza*, SNUC) had been instituted by Federal Law 9.985 in July 2000, it was the mid to late-2000s that marked a period of extensive expansion of protected territory. As shown in Figure 3, from 2004 through 2009, over 180,000 square kilometers of federal and state areas of integral protection were created in the Legal Amazon. Approximately 80% of this growth occurred in the 2004 through 2005 period. Significant progress was also made in the official recognition of indigenous lands (May et al. (2011)). Moreover, as of 2005, the Federal Government could declare special Areas of Provisional Administrative Limitations (*Área de Limitação Administrativa Provisória*, ALAP). The concept, introduced by Provisional Executive Order 238 in February 2005 and later approved in the July 2005 Federal Law 11.132 as an amendment to Federal Law 9.985/2000, enabled the temporary restriction of threatening activities in territory being considered for the establishment of new protected areas.

Figure 3: Total federal and state protected areas in the Legal Amazon



Notes: Authors' elaboration based on data from the National Registry of Conservation Units (Cadastro Nacional de Unidades de Conservação, CNUC/MMA)

The launch of the PPCDAm in 2004 introduced a new form of dealing with deforestation in the Legal Amazon. From that moment on, conservation efforts were based on integrated action and participation of the highest levels of the Federal Government (Ipea et al. (2011)). Never before had numerous Ministries been simultaneously involved with combating deforestation, an issue previously restricted to the MMA and Ibama agendas (IPAM (2009)). Moreover, the mobilization of key organizations particularly 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 allowed for the implementation of innovative procedures for monitoring, environmental control, and territorial management (IPAM (2009)).

2.2 Presidential Decrees and Resolutions, 2007-2008

The second turning point in Brazilian environmental legislation began with the signing of Presidential Decree 6.321 in December 2007. Unlike the PPCDAm, which had been designed as a comprehensive conservation program, Presidential Decree 6.321/2007 established the legal basis for singling out municipalities with very high deforestation rates and taking differentiated action towards them. In January 2008, the MMA published Ordinance 28, listing thirty-six municipalities classified as in need of priority action to prevent, monitor, and combat illegal deforestation. The identification of these priority municipalities was based on the following three criteria: (i) total deforested area; (ii) total area deforested in the past three years; and (iii) an increase in deforestation rate in at least three of the past five years. Any municipality in the Legal Amazon could be included in the list of priority municipalities, which was to be periodically updated by the MMA.

With the approval of Presidential Decree 6.321/2007, rural establishments in priority municipalities became subject to stricter command and control policies and more rigorous monitoring of irregular activity. Specific measures adopted in these areas included, but were not limited to, harsher registration, licensing and georeferencing requirements, as well as the revision of private land titles, so as to identify fraudulent documents and illegal occupations.

Command and control within the Legal Amazon was further affected by the passing of Presidential Decree 6.514 in July 2008, which revoked the 1999 Presidential Decree 3.179 and reestablished directives regarding the federal administrative processes for the investigation of environmental infractions and their respective sanctions. By making it simpler to sell confiscated assets in public auctions and reducing the number of defence instances allowed during administrative processes against environmental criminals, the new decree enabled such processes to be completed more quickly (Barreto et al. (2008)).

Credit policies also underwent significant revisions in the late 2000s. Previous legislation had already determined that economic activities in areas that suffered from illegal deforestation or irregular burning of natural vegetation were to be embargoed. With the passing of Presidential Decree 6.321/2007, official federal credit agencies were forbidden to approve credit of any kind not only to agricultural or forest activities performed within such areas, but also to any service and commercial or industrial activity that involved the acquisition, intermediation, transport, or commercialization of goods produced in embargoed establishments. In February 2008, the National Monetary Council (*Conselho Monetário Nacional*, CMN) approved Resolution 3.545,

which determined that rural credit for agricultural activities in the Amazon biome was to be conditional, obligatorily as of July 2008, upon the presentation of proof of the borrower's compliance with environmental legislation and legitimacy of land claims.⁴

In 2008, Brazilian environmental legislation took a new turn as measures from Presidential Decree 6.321/2007, MMA Ordinance 28/2008, and CMN Resolution 3.545/2008 were implemented. The targeting of municipalities with critical rates of deforestation was henceforth legally and operationally viable, and the conditioning of rural credit upon environmental regularity represented a novel approach to credit policies.

The 2004 and 2008 turning points coincide with subsequent decreases in the recorded rate of deforestation in the Legal Amazon (see Figure 1). However, separating the effects of conservation policies from the effects of agricultural commodity prices and of other potential drivers of the deforestation slowdown remains an empirical challenge.

3 Conceptual Framework

This section introduces the conceptual framework we use to study the relationship between agricultural commodity prices, conservation policies, and deforestation. The model presented below describes a simplified situation in which a farmer seeking to increase his agricultural production may do so by expanding his farmland beyond his original landholding. It focuses on the extensive margin of agricultural production. In particular, the model shows how conservation policies may influence the farmer's optimal choice of farmland size, as well as his response to changes in agricultural commodity prices.

3.1 Model

Consider a farmer having \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.

4 Alterations to CMN Resolution 3.545/2008 were made by Resolutions 3.583/2008, 3.599/2008, 3.618/2008, 3.890/2010, and 3.926/2010.

5 In this model, agricultural activities may refer to the cultivation of cropland, the use of land as pasture for livestock, or a combination of both.

For each hectare of land used over \bar{T} , in addition to the cost of clearing the new area, the farmer faces a risk of paying penalties that depends on the stringency of conservation policies. We express the shadow cost of expanding farmland beyond \bar{T} as $\Gamma > 0$. This represents the combination of clearing costs and expected monetary infringement costs associated with the use of areas of public forest. In this formulation, Γ is a policy parameter.

Agricultural output is determined by the production function $Y = AT^\beta$, which depends on farmland T and a productivity parameter A . 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's objective is to choose farmland so as 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 $T^* \leq \bar{T}$. This price 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 is given by:

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

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) shows the optimal farmland size to be chosen by the farmer 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 ($T^* < \bar{T}$). 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 the concentration point \bar{T} results from the fact that, at \bar{T} , the marginal per hectare cost of land discontinuously jumps from 1 to $(1 + \Gamma)$ and remains above the marginal revenue up to the point at which output price equals \bar{P}_2 . Notice 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 last scenario, agricultural output prices are high enough to make production optimal at levels of $T^* > \bar{T}$, despite the higher costs of production.

The next subsections examine the model's main policy implications for land use from both a theoretical and an empirical perspective.

3.2 Policy Effects on Land Use: Theoretical Implications

In the model's simplified setting, deforestation is defined as the act of clearing areas of public forest in order to use the land for agricultural production. All land area beyond the farmer's property - that is, beyond \bar{T} - is public forest. Consequently, as long as output prices are high enough to induce the clearing of previously unused land, comparative statics for optimal farmland size are entirely 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. Formally, the effects of an increase in policy stringency on optimal farmland size are given by:

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

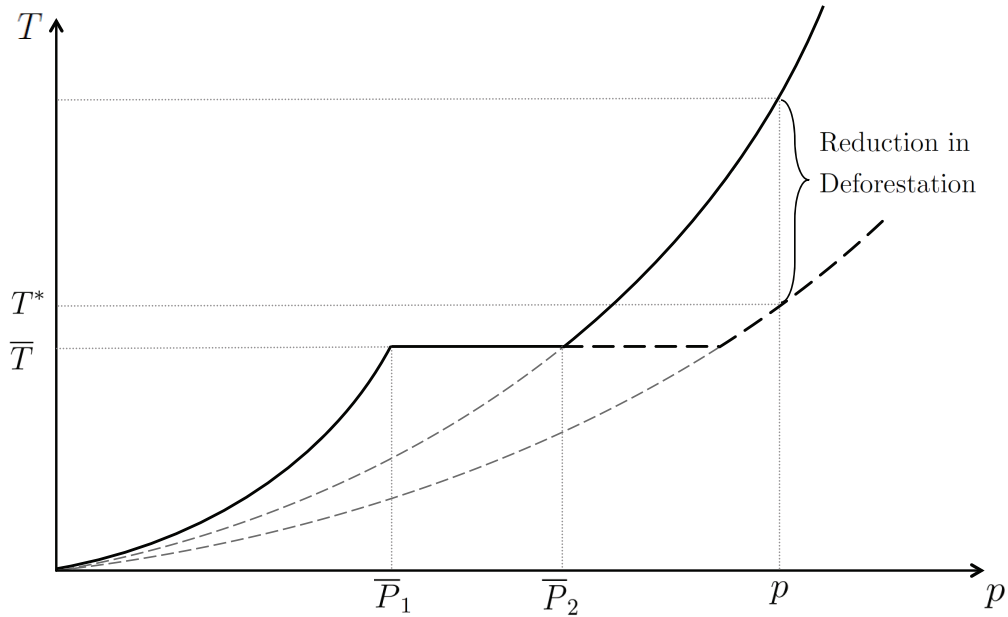
Equation (3) states that when output prices are low ($p \leq \bar{P}_2$), variations in policy stringency have no effect on optimal farmland size. This is because relatively low output prices do not encourage a farmer to extend production beyond his property ($T^* \leq \bar{T}$). In this case, there is no incentive to clear areas of public forest and thus no deforestation. However, when output prices are sufficiently high ($p > \bar{P}_2$) for the farmer's optimal farmland choice to imply engaging in forest clearings ($T^* > \bar{T}$), stricter policies ($d\Gamma > 0$) negatively impact optimal farmland size. As a result, increased policy stringency alleviates the pressure on public forests and restrains deforestation. Figure 4 illustrates this point.

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 are calculated as the derivative of Equation (3) with respect to output prices and are formally given by:

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

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 ($p \leq \bar{P}_2$), stricter policies weaken this relationship for sufficiently high output prices ($p > \bar{P}_2$). This effect is illustrated in Figure 4, which shows that an increase in policy stringency alters the curve relating output prices and optimal farmland size for all $p > \bar{P}_2$, making it flatter. Higher policy stringency therefore decreases the elasticity of optimal land use choice with respect to output prices.

Figure 4: Policy effect on optimal farmland size



Finally, although policy stringency has no effect on land use when the farmer operates within his own boundaries ($T^* \leq \bar{T}$), it does impact marginal costs at \bar{T} , since $\bar{P}_2 = (1 + \Gamma)\bar{P}_1$. Indeed, as Γ increases, the distance between \bar{P}_1 and \bar{P}_2 widens. From an economic perspective, this means that higher policy stringency enlarges the discontinuity in per hectare cost of land at the concentration point \bar{T} . Thus, by sufficiently driving up the value of the relevant threshold \bar{P}_2 , stricter policies restrain 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 farmland size and deforestation depends on agricultural output prices. If output prices are low ($p \leq \bar{P}_2$), policies do not affect optimal farmland size and there is no deforestation. If output prices are high ($p > \bar{P}_2$), farmers are induced to expand their farmland by clearing areas of public forest and thus engaging in deforestation. In this second scenario, conservation policies exert both a direct and an indirect effect on deforestation in the sense that increased stringency of such policies:

- Reduces optimal farmland size,

$$\frac{dT^*}{d\Gamma} < 0, \text{ if } p > \bar{P}_2 \text{ (or } T^* > \bar{T}\text{); and } \frac{dT^*}{d\Gamma} = 0, \text{ otherwise;}$$

and,

- Weakens the relationship between agricultural output prices and forest clearings,

$$\frac{d^2T^*}{d\Gamma dp} < 0, \text{ if } p > \bar{P}_2 \text{ (or } T^* > \bar{T}\text{); and } \frac{d^2T^*}{d\Gamma dp} = 0, \text{ otherwise.}$$

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

Table 1: Price and policy effects on optimal farmland size - comparative statics

	Optimal Farmland Size (T^*)		
	$p < \bar{P}_1$	$\bar{P}_1 \leq p \leq \bar{P}_2$	$p > \bar{P}_2$
Price (dp)	+	0	+
Policy ($d\Gamma$)	0	0	-
Price*Policy ($dpd\Gamma$)	0	0	-

3.3 Policy Effects on Land Use: Empirical Implications

Assuming we have a sample of municipalities with information over time about deforestation rates, prices, and policies, how can the model help us structure the empirical analysis of conservation policies? What are the main challenges and possible solutions implied by it? The theoretical implications presented previously can be mapped onto empirical implications that aid in answering these questions. Two such implications are particularly relevant for the following sections.

First, the model states that agricultural output prices must be included in the analysis of the effects of conservation policies. Since the pressure to clear new areas is affected by agricultural prices, the observed effectiveness of policy varies according to prices. In particular, if a new set of policy measures is implemented in a period of decreasing agricultural prices, it might not be possible to capture the effects of such policies until agricultural prices recover. This is one of the empirical challenges we face when attempting to estimate the relative contribution of policies and prices to the dynamics of deforestation. In order to better identify the policy impact, we must therefore control for prices.

This implication also has consequences for the design of public policies. For instance, in order to keep the deforestation rate constant (e.g., equal to zero), the required efforts of command and control policies should vary in the same direction as agricultural prices.⁶ As another example, consider policies that take the form of payments for environmental services, such as some Reducing Emissions from Deforestation and Forest Degradation (REDD+) policies. As the shadow price of preserving the forest varies with agricultural prices, the compensation scheme should also vary accordingly.

⁶ In this conceptual framework, we consider a simplified case in which the relationship between prices and agricultural production is contemporaneous. However, in a richer setting with leads and lags, this implication should be adapted. This is particularly clear for the case of cattle ranching, where the contemporaneous correlation is expected to be negative.

Second, the model predicts that the effect of conservation policies is influenced not only by agricultural prices, but also by the relative tightness of the land constraint. The smaller the size of land available for 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 available and unavailable land.⁷

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 the area unavailable for agriculture (which includes areas of public forest) and total area in each municipality. This variable depends on the municipality land endowment, a relatively fixed or slowmoving municipality feature. This proxy is valid because, for a given municipality, the greater the calculated ratio, the smaller the relative landholding sizes and the tighter the relative constraint faced by farmers. Second, we can use observed deforestation rates 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.

4 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. This selection refers to the four states that had at least one of their municipalities classified as a priority municipality in MMA Ordinance 28/2008. It is further restricted to those municipalities for which there was variation in forest cover during the period. The final sample comprises 380 municipalities. The following sections describe the exercise's main variables.

4.1 Deforestation

Data on deforestation is built from satellite-based images that are processed at the municipality level and publicly released by INPE's Project for Monitoring Deforestation in the Legal Amazon (Projeto de Monitoramento do Desflorestamento na

⁷ Unavailable land refers to territory occupied by public forests, bodies of water, or constructions, as well as to regulated areas and degraded land.

Amazônia Legal, PRODES/INPE). In our analysis, deforestation is defined as the annual deforestation increment, which is 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 measures the area in square kilometers deforested between the 1st of August of $t - 1$ and the 31st of July of t .

For any given municipality, cloud cover during the period of remote sensing may compromise the accuracy of satellite images and thus require images to be produced at a different time. As a result, image records for different years may span from less to more than twelve months. To control for measurement error, variables indicating cloud cover and other unobservable areas are included in all regressions.

To smooth the cross-sectional variation in deforestation due to heterogeneity in municipality size, we use a normalized measure of the annual deforestation increment. Note that in using a normalized variable, we also address the second empirical implication of our model, which establishes that T is a municipality-specific measure of land constraint. The normalization ensures that our analysis considers relative variations in deforestation increments within municipalities, thereby taking into account the relative nature of T . The variable is constructed according to the following expression:

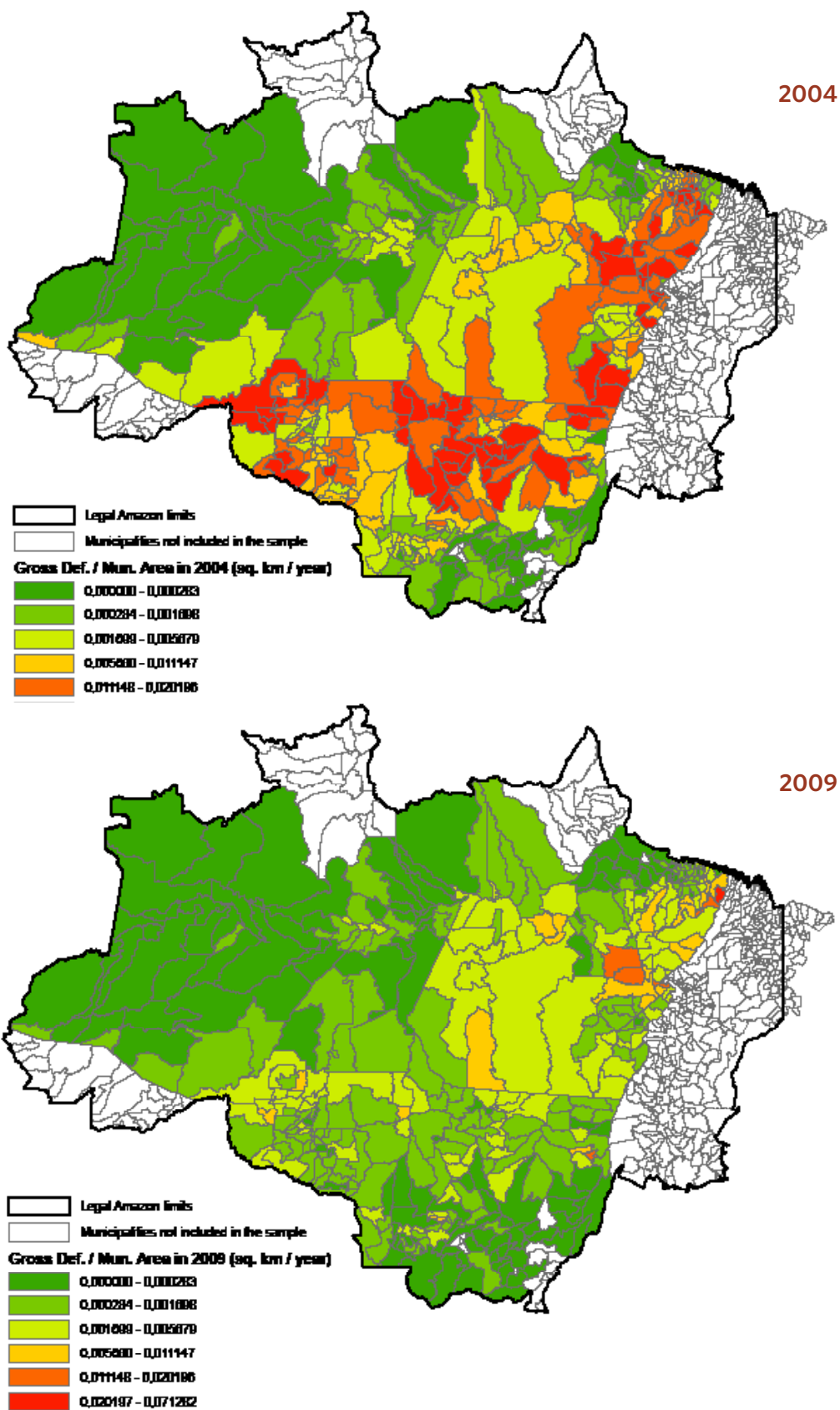
$$D_{it} = \frac{ADI_{it} - \overline{ADI_{it}}}{sd(ADI_{it})} \quad (5)$$

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 the 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.

Figure 5, which presents deforestation figures for 2004 and 2009, indicates that the reduction in deforestation rates was observed over a large area of the sample states. Although relatively concentrated in municipalities along the agricultural frontier, the size of this area illustrates the challenge faced by conservation policies.

⁸ We use deforestation increment because municipality-level deforestation rates are not available from PRODES/INPE for the period of interest.

Figure 5: Gross deforestation increment per municipal area



4.2 Agricultural Prices

Agricultural commodity prices were collected at the Agriculture and Supply Secretariat of the State of Paraná (*Secretaria de Agricultura e do Abastecimento do Estado do Paraná*, SEAB-PR). The set of commodity prices includes prices for beef cattle, soybean, cassava, rice, corn, and sugarcane. Soybean, cassava, rice, and corn are predominant crops in terms of harvested area in the Legal Amazon. Although not a predominant crop in the region, sugarcane is also included to account for concerns about the recent expansion of Brazilian ethanol biofuel production. Together, the five crops account for approximately 70% of total harvested area averaged across sample years.

Agricultural prices are endogenous to local agricultural production. Figure 6 shows that the Paraná (a southern Brazilian state) price series are highly correlated with average local crop prices calculated for the Legal Amazon sample municipalities. Hence, we use the Paraná price series as exogenous indicators of local market conditions within our empirical context.

The Paraná price series are used to build two variables of interest. The first of these variables, an annual index of crop prices, is constructed in three steps. First, we calculate 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 and are expressed as an index with base year 2000.

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

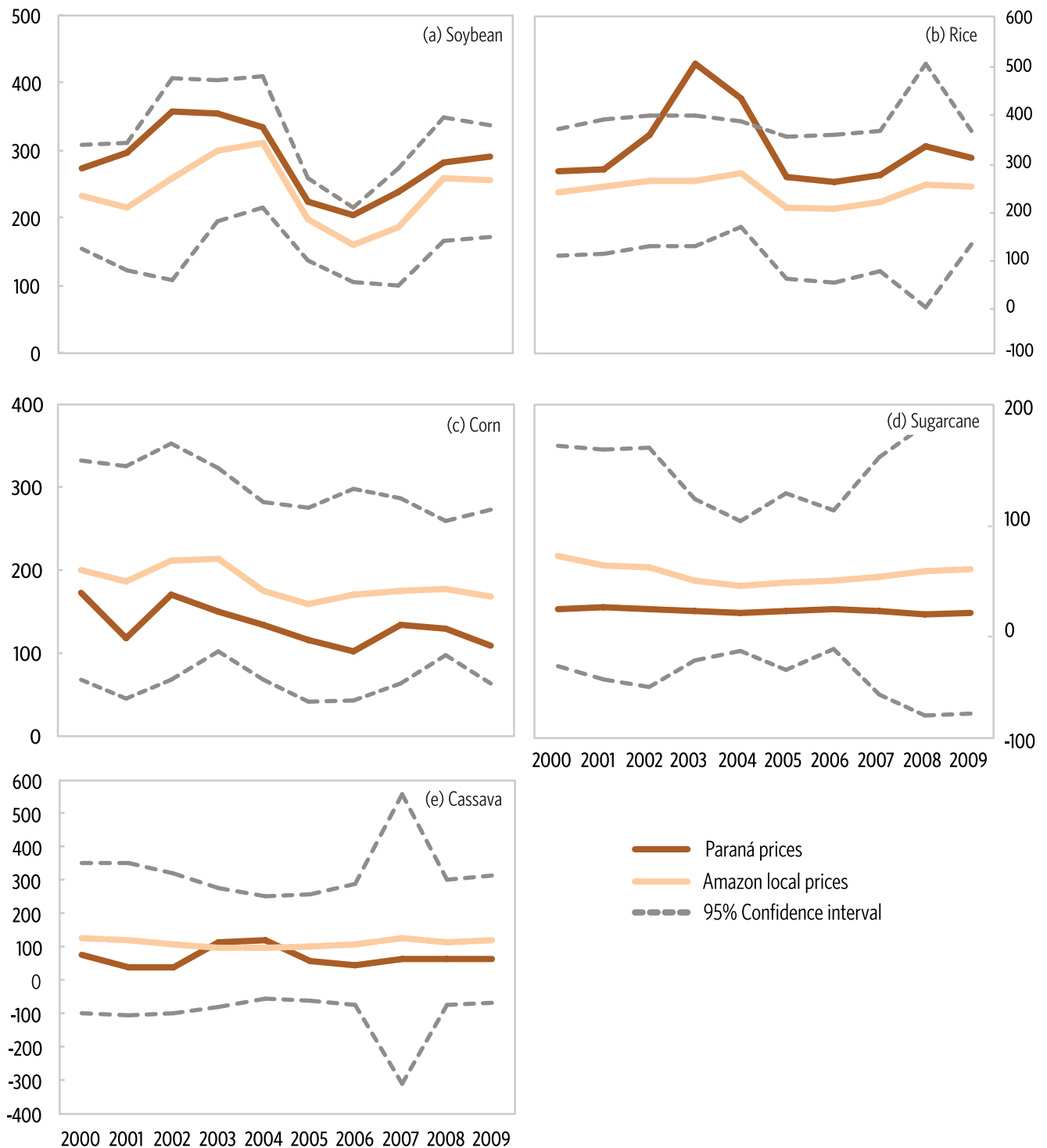
$$PPA_{itc} = PP_{tc} * A_{ic,2000-2001} \quad (6)$$

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.⁹ This latter term captures the relative importance of crop c within municipality i 's agricultural 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.

Third, we use principal component analysis on the weighted real crop prices to derive our first variable of interest, the annual index of crop prices. This technique allows the price variations that are common to the five selected crops to be represented in one single measure. The resulting index of crop prices captures the first principal

⁹ Variables on annual municipality crop production (harvested area, quantum, or value in current prices) is based on data originally from the Municipal Crop Survey of the Brazilian Institute for Geography and Statistics (Pesquisa Agrícola Municipal do Instituto Brasileiro de Geografia e Estatística, PAM/IBGE).

Figure 6: Paraná price series and average local prices



Notes: Authors' elaboration based on data from SEAB-PR and PAM/IBGE.

component of the five weighted real prices. The first column of Table 2 shows the weights on each crop price that yield the first principal component used in the analysis. The first principal component explains approximately 38% of the variation in the series, driven mostly by soybean, rice, and corn.

Table 2: The annual index of crop prices and descriptive statistics

	Weights of 1st Component of PCA	Sown Area as Share of:					
		Total Municipality Area			Total Municipality Sown Area		
		2002	2009	Difference	2002	2009	Difference
Soybean	0.594	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	-0.07
Corn	0.6362	0.0067	0.0101	0.0034	0.2867	0.283	-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	0.344	0.368	0.024

Notes: Agricultural price data originally from SEAB-PR, and municipality agricultural production data originally from PAM/IBGE. Sample includes 380 municipalities located in the states of Amazonas, Mato Grosso, Pará, and Rondônia.

The use of the annual index of crop prices addresses our model's first empirical implication, which establishes that agricultural output prices should be included in conservation policy evaluation. 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 for this analysis 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 land pasture is not observable, in this case $A_{ci,2000-2001}$ is the ratio of heads of cattle to municipal area in municipality i averaged over the 2000 through 2001 period.

4.3 Policies

As discussed in Section 2, two turning points marked the Brazilian environmental policy context in the 2000s. First, in 2004, the PPCDAm inaugurated a novel approach of integrated action and high-level participation to coordinate the strengthening of command and control strategies and the creation of new protected areas. Second, in 2008, the targeting of municipalities with critical rates of deforestation in the Legal Amazon became viable, and rural credit for agricultural activities in the Amazon biome became conditional upon the presentation of proof of the borrower's compliance with environmental regulations. We therefore assume that conservation policy stringency increased discontinuously beginning in 2004 and, again, beginning in 2008.

The conceptual framework presented in Section 3 states that conservation policies are binding whenever optimal farmland size exceeds that of the farmer's landholding. Consequently, such policies should be particularly effective in localities where land constraints are tight. Given this result, we derive policy variables based on interactions between: (i) the 2004 and 2008 turning points, represented by dummy variables indicating either $Post2004 = 1$ (year > 2004) or $Post2008 = 1$ (year > 2008); and (ii) a proxy for tightness of land constraints at the municipality level, which introduces cross-sectional variation into our policy variables.

We explore the two alternative proxy variables for tightness that, as argued in Section 3.3, are suggested by the model's empirical implications. The first proxy uses data from the 2006 Agricultural Census to measure the amount of unavailable land beyond farmland relative to each municipality's total area. It is calculated as:

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

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 of rural establishments in municipality i in 2006; and $Unsuitable_i$ is the area unsuitable for agricultural activity within rural establishments in municipality i in 2006. Areas classified as unsuitable for agricultural activity include legal reserves and areas of permanent protection, degraded land, unviable land, and areas dedicated to constructions within the rural establishment. The larger the value of $Tight_i$, the smaller the relative size of available land for agriculture within rural establishments in municipality i , and hence the tighter the land constraint in that municipality.

The second proxy is defined as $D_{i,2004}$, the normalized annual deforestation increment for each municipality i in $t = 2004$. As the deforestation increment recorded for 2004 refers to the 2003 peak of agricultural commodity prices, $D_{i,2004}$ captures how binding the land constraint was in 2004, or how close farmers were to T at the time. This variable depends on conjunctural price fluctuations, which are potentially noisy and can introduce measurement error. This alternative proxy is used for robustness checks.

The final policy variables are given by $Tight_i * Post2004$ and $Tight_i * Post2008$, or $D_{i,2004} * Post2004$ and $D_{i,2004} * Post2008$.

5 Empirical Model

In order to examine the contribution of conservation policies to the 2000s Legal Amazon deforestation slowdown, we use the following municipality fixed effects specification:

$$D_{it} = \alpha_i + \phi_t + \beta_1 M_{it} + \beta_2 P_{i,t-1} + \beta_3 (Tight_i * Post2004) + \beta_4 (Tight_i * Post2008) + \epsilon_{it} \quad (8)$$

where D_{it} is defined by Equation (5) as 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. In order 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 4.2. 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, in order to maximize 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 from mid- $t-1$ onwards. Prices in $t-1$ should thus be associated with forests cleared between August of $t-1$ and July of t . We 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 6.1.

As $P_{i,t-1}$ is based on an interaction between price trends and municipality farmland use before 2002, the coefficient β_2 captures the exogenous effect of variations in the price indices on the municipal deforestation increment over the 2002 through 2009 period. The policy variables $Tight_i * Post2004$ and $Tight_i * Post2008$ absorb the remaining withinmunicipality variation in the deforestation increment between the years before 2004 (or 2008) and those afterwards. We enable the policy effect to be heterogeneous on tightness of land constraint since our conceptual model suggests 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 commodity price trends at the municipality level, but also on common and municipality-specific time trends.

In more complete specifications, we also include interactions between the annual index of crop prices and policy variables in order to test whether policy influences the relationship between agricultural prices and deforestation. As discussed in Section 3.2, we expect policy stringency to impact this relationship by lowering the price elasticity of optimal farmland size when production is set beyond T . All regressions include variables controlling for unobservable areas during the period of remote sensing. Robust standard errors are clustered at the municipality level to account for serial correlation in error terms.

6 Deforestation Slowdown: Prices or Policies?

In this section we present this paper's 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 impacted the pace of forest clearings in the Legal Amazon, controlling for different types of variations in prices and municipality-specific time trends. Finally, we use counterfactual simulations based on our full regressions to quantify the contribution of conservation policies to the deforestation slowdown of the 2000s in terms of avoided forest clearings and loss of carbon storage.

6.1 The Effect of Crop and Cattle Prices on Deforestation

Table 3 presents the relationship between deforestation and both the annual index of crop prices and the cattle price index (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

Table 3: 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)***	-0.02 (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)	0.01 (0.006)*	0.01 (0.006)*	0.01 (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: Dependent variable is the annual normalized deforestation increment at the municipality level. 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 Rondonia, and it is further restricted to those municipalities with variation in forest cover during the period. 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.

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 the following three columns of Table 3, we explore the relationship between deforestation and the timing of the variations in crop prices. In column 2, we use as regressor the annual index of crop prices calculated only for the calendar months 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, the 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 is consistent with farmers making decisions about land use and forest clearings before the sowing period. In Section 7 we discuss the potential caveats associated with this result and perform robustness checks. Placebo tests confirm that we are indeed accurately capturing the timing of the relationship between prices and deforestation.

Finally, the last columns of Table 3 include as regressors the crop price indices per culture as defined in Equation (6). We find positive and robust associations between soybean, rice, and corn prices and deforestation. There is no significant relationship between sugarcane prices and deforestation, 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.

6.2 The Effect of Policies on Deforestation

In column 1 of Table 4, we regress the normalized deforestation increment on the policy variables $Tight_i, Post2004$ and $Tight_i, Post2008$, conditional on 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 due to 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 4, we add interactions between policy variables and crop prices. We are now controlling for different sources of price variations and potential heterogeneity in policy effectiveness. In short, we allow policies to affect deforestation responses to prices, as implied by our model. Our conceptual framework suggests that policy stringency impacts 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 7 provide further support for this result. In particular, we find that the results are robust when using alternative proxy variables for $Tight_i$ as well as alternative price variables.

6.3 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 carbon storage loss. Our baseline specification is the one presented in column 5 of Table 4, which includes the full set of fixed effects, specific time trends, and price interactions. This specification delivers the predicted trend in deforestation

Table 4: 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)***	0.06 -0.247	0.075 -0.273	0.076 -0.269
Cattle Price Index (current)	-0.025 (0.006)***	0.003 -0.01	0.001 -0.01	0.001 -0.01	0.001 -0.01
Cattle Price Index (lagged)	0.033 (0.006)***	-0.012 -0.009	-0.01 -0.009	-0.01 -0.009	-0.01 -0.009
Tight*Crops Price Index			0.447 -0.469	0.495 -0.521	0.491 -0.517
Crops Price Index*Post2004			0.009 -0.15		-0.003 -0.148
Crops Price Index*Post2008				-0.046 -0.118	-0.047 -0.11
Tight*Crops Price Index*Post2004			-0.012 -0.299		-0.02 -0.3
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: Dependent variable is the annual normalized deforestation increment at the municipality level. 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, and it is further restricted to those municipalities with variation in forest cover during the period. 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.

increment for each sample municipality, as defined by:

$$\begin{aligned} \hat{D}_{it} = & \hat{\alpha}_i + \hat{\phi}_i + \hat{\beta}_1 M_{it} + \hat{\beta}_2 P_{i,t-1} + \hat{\beta}_3 (Tight_i * Post2004) \\ & + \hat{\beta}_4 (Tight_i * Post2008) + I_{it} \hat{\beta}_5 \end{aligned} \quad (9)$$

where D_{it} is the predicted deforestation increment, calculated by using the estimated coefficients represented by the hatted parameters. The last term on the right hand side of Equation (9), I_{it} , represents the full set of interactions between prices and policies.

Given the hatted parameters, we are able to recalculate each 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 situation where conservation policies introduced after both the 2004 and the 2008 policy turning points had not been implemented. We then accumulate D_{it} across all 380 sample municipalities for each year to calculate the total deforestation increment over time in the absence of such policies.

Column 1 of Table 5 shows the total observed deforestation trend for the 2002 through 2009 period. In column 2, we present the counterfactual trend as if conservation policies introduced following both the 2004 and the 2008 policy turning points had not been implemented. 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 for the 2005 through 2009 period. 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 total deforestation that would have occurred in the 2005 through 2009 period in the absence of such policies. Using the conversion factors of 10,000 tons of C per square kilometer and 5 US dollars per ton of CO_2 mentioned in MMA (2011), this avoided deforestation is equivalent to an avoided loss of 621 million tons of stored C, or 2.3 billion tons of stored CO_2 , which is valued at 11.5 billion US dollars.

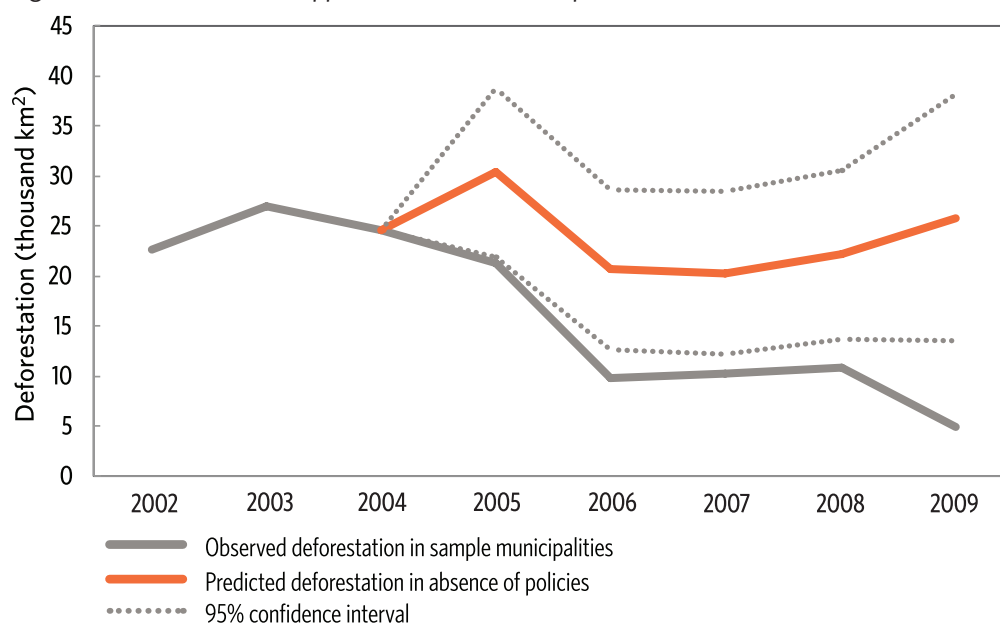
Figure 7 plots the observed (column 1) and simulated (column 2) deforestation trends over the period of interest. The dotted lines give a 95% confidence interval to the simulated trend. Avoided deforestation is estimated at around 10,200 square kilometers per year for 2005 through 2008, and at more than 20,000 square kilometers in 2009. It is also noteworthy that deforestation would have reached another peak 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

Table 5: Counterfactual simulations

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
Sum 2005-2009	57,144	119,182
Avoided Deforestation 2005-2009 (in km2)	-	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 4, which includes the full set of fixed effects, specific time trends, and price interactions. Simulation 2 uses specification in column 6 of Table 4 instead. Both specifications are 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, and is further restricted to those municipalities with variation in forest cover during the 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.

Figure 7: What would have happened in the absence of policies? - counterfactual simulation



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 Caveats and Robustness Checks

The empirical strategy behind specification (8) relied on two important identification cornerstones. First, our strategy controls for direct price effects and municipality specific time trends. This depends crucially 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 in order 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 7.1, we use placebo tests in order to check whether we are indeed capturing the relevant relationship between price variations and deforestation.

Second, 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 area unavailable for agriculture and total area in each municipality. This proxy should be valid because, for a given municipality, the greater the calculated ratio, the smaller the relative landholding sizes and the tighter the relative constraint faced by farmers. However, detailed information on land use and landholding sizes is available only from 2006 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. Yet, our conceptual framework provides an alternative way to build a proxy for the tightness of land constraints at the local level. As discussed in Section 3.3, an increase in agricultural prices will push for larger optimal farmland size and thereby make the relative land constraint tighter. In Section 7.2 we explore this by using the observed deforestation rates during 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.

Table 6: The timing of price variation and deforestation rates: placebo regressions

	Annual Normalized Deforestation Increment			
	(1)	(2)	(3)	(4)
Crops Price Index (t-1)	0.39 (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: 1 st 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)	0.18 (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: Dependent variable is the annual normalized deforestation increment at the municipality level. 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, and it is further restricted to those municipalities with variation in forest cover during the period. 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.

7.1 The Timing of Price Variations and Deforestation

In Table 6 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 is used in Table 3, columns 1 through 4. In column 1 of Table 6 we add as regressors future ($t + 1$) and past ($t - 2$) crop prices. As in Table 3, we confirm that deforestation is associated positively 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 3, we find that deforestation is positively and significantly associated with variation in crop prices before the sowing season of $t - 1$ (columns 2 and 3), while no significant impact is found for crop price variations before the sowing seasons of $t + 1$ or $t - 2$. In the last column we confirm that price variations during the sowing season are not associated with forest clearings. This set of results is consistent with farmers making decisions on land use and forest clearings just before the sowing season of $t - 1$. This is therefore the relevant source of crop price variation that has to be controlled for in our analysis.

7.2 Alternative Proxy Variables for Tightness

Column 1 of Table 7 repeats the baseline specification found in column 2 of Table 4. In the following two columns 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 4.3. In columns 4 and 5 we add to specifications in columns 2 and 3, respectively, interactions between policies and prices in order 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 7, 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.¹⁰ Counterfactual total deforestation is estimated at 84,100 square kilometers had the set of conservation

¹⁰The smaller effect can potentially be driven by measurement error in tightness, as $D_{i,2004}$ is a response to conjunctural price fluctuations.

Table 7. 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)***	-0.74 (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)***	-14.18 (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	-50.26 (12.161)***	-4.763 -2.984	-16.804 (4.679)***
Cattle Price Index (current)	0.003	-0.002	-0.019	-0.003	-0.017	0.274	0.433	-0.128
Cattle Price Index (lagged)	-0.01	-0.009	(0.008)**	-0.009	(0.008)**	-0.275	(0.248)*	-0.206
	-0.012	-0.005	0.008	-0.004	0.009	-0.307	-0.508	-0.06
	-0.009	-0.008	-0.006	-0.008	-0.006	-0.277	(0.233)**	-0.183
Tight*Crops Price Index				0.246	0.277	109.641	2317	14.005
				-0.158	(0.114)**	(27.952)***	(10.346)**	(3.956)***
Crops Price Index*Post2004				-0.031	0.177	-2.977	-3.993	-0.909
				-0.053	(0.107)*	-7.388	(0.908)***	-1.462
Crops Price Index*Post2008				-0.067	0.029	5.951	1172	5.877
				(0.032)**	-0.044	-4.966	-1.487	(1.740)***
Tight*Crops Price Index*Post2004				0.057	-0.072	-0.045	1.292	0.885
				-0.108	-0.063	-16.842	-3.855	-0.898
Tight*Crops Price Index*Post2008				-0.012	-0.018	-10.394	-0.294	-2.042
				-0.067	-0.026	-10.068	-2.934	(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> pc75%	Tight= Deforestation in 2004	Tight= Dummy: Baseline> pc75%	Tight= Deforestation in 2004	Tight= Baseline	Tight= Dummy: Baseline> pc75%	Tight= Deforestation in 2004

Notes: Dependent variable is the annual normalized deforestation increment at the municipality level. 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 Rondonia, and it is further restricted to those municipalities with variation in forest cover during the period. 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.

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 in the 2005 through 2009 period in the absence of such policies in this alternative simulation. Using the MMA (2011) conversion factors of 10,000 tons of C per square kilometer and of 5 US dollars per ton of CO₂, this is equivalent to an avoided loss of 270 million tons of stored C, or 991 million tons of stored CO₂, valued at 5.0 billion US dollars.

8 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 Legal Amazon. Our results suggest that changes to Brazilian environmental policies have had a sizeable direct impact on deforestation levels and have thereby curbed forest clearings. It is important to note that 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.

Our 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. Using the MMA (2011) conversion factors of 10,000 tons of C per square kilometer and of 5 US dollars per ton of CO₂, this is equivalent to an avoided loss of 621 million tons of stored C, or 2.3 billion tons of stored CO₂, valued at 11.5 billion US dollars. Analogous calculations for an alternative simulation confirm the sizeable impact of policies.

Overall, our results show that: (i) deforestation rates are indeed responsive to agricultural output prices; (ii) changes to conservation policies implemented beginning in 2004 and 2008 significantly contributed to the curbing of deforestation rates, even after controlling for different sorts of price effects; and (iii) counterfactual simulations suggest that the policies introduced following the 2004 and 2008 policy turning points avoided substantial forest clearings in the Amazon from 2005 through 2009.

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