# ABSTRACT

WU, YU. Essays on Deforestation and Forest Ecosystem Services: An Economic Perspective. (Under the direction of Erin O. Sills).

The recognition of deforestation as a major source of carbon emissions has invigorated worldwide efforts to reduce deforestation. Yet questions remain about whether these efforts have been effective in reducing deforestation and, if so, which interventions have been most effective. One reason for this uncertainty is that decision-making and the drivers of deforestation change over time as the frontier evolves.

The first essay in my dissertation examines this evolution by modeling deforestation using an 18-year panel on 8,770 farm properties in a typical agrarian settlement established by the Brazilian federal government in the Amazonian State of Rondônia. Previous studies throughout the tropics have found that market access—one of the key drivers of deforestation—is positively correlated with deforestation. This relationship has been attributed to the effect of market access on farm-gate prices for agricultural and/or timber products. However, access to markets also means access to urban centers, which has multiple influences on household decisions. I incorporate these multiple dimensions of urban access into a household production framework and demonstrate that their combined effect on deforestation is ambiguous and can change over time. I test whether the effect of distance to cities has changed over time in the study region.

Specifically, I test for structural shifts in the relationship between distance to cities and deforestation. Estimation results for a two-part, within-between random effects model show that after controlling for forest stock and other drivers of deforestation, the relationship between distance to cities and deforestation changed from negative to positive around 2004. Further investigation suggests that the diminishing role of transportation cost in farm-gate price,

combined with increasing enforcement of environmental laws and labor market opportunities in the urban center, triggered the change in effect of distance on deforestation from negative to positive. Another reason for this uncertainty is lack of information on the local benefits and costs of clearing the forests. Quantifying forest ecosystem services on a local scale will clarify whether and how these should be incorporated into policy decisions.

The second essay investigates whether forests deliver economic benefits to local farmers through watershed services—and the value of those services—in the same study region as the first essay; this region has some of the highest rates of deforestation and a large fraction of the farming population in the Brazilian Amazon. The farmers in my study site who benefit from watershed services also typically own and make land use decisions for part of that watershed. I therefore extend the standard theoretical framework to account for the endogeneity of land use decisions on the property. I demonstrate that even with this modification, the marginal value of watershed services is equal to the marginal profits from these services. Empirically, I find that the amount of forest in the watershed off lot does not influence productivity or net farm revenues when water is abundant. However, when water is scarce—i.e. in small watersheds and drought years—milk production is higher on farms with mature forest upstream off lot than on those that are downstream from deforested land. This suggests that in this relatively flat, humid tropical region, a forested drainage provides a form of insurance against drought. The effects of upstream mature forest cover on lot have mixed effects on downstream milk production, and are not endogenous in the milk production system. Involving and dividing the effects of upstream forest within and outside the farm lot yields vital information about the local beneficiaries and cost bearers of forest watershed services.

# Essays on Deforestation and Forest Ecosystem Services: An Economic Perspective

by
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# DEDICATION

To my entire family.

# BIOGRAPHY

Yu Wu was born and raised in Yunnan Province, southwest China. She earned her bachelor's degree in Agricultural and Forest Economics from Beijing Forestry University (BFU) in Beijing, China, in 2012. At BFU, she received the Outstanding Bachelor's Thesis Award, the Outstanding Academic Performance Fellowship (twice), and the Liang Xi Fellowship (four times). In 2014, Yu earned a master's degree in Economics at North Carolina State University (NCSU). In the same year, Yu received the Provost's Doctoral Recruitment Fellowship from NCSU and began her doctoral studies in Economics under the direction of Dr. Erin Sills. Her major research fields are environmental and resource economics and agricultural economics. During her doctoral work, she was a research assistant and teaching assistant at the Center for Environmental and Resource Economic Policy at NCSU. Yu has been appointed a Postdoctoral Research Associate in the Carolina Population Center at the University of North Carolina–Chapel Hill, which she will begin in Fall 2018.

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Finally, I would like to thank my family and friends for their support and encouragement. My husband, Renzun, accompanied me on this challenging and exhilarating journey; I am grateful to have him to share my laughter and tears. I wish to give special thanks to my parents, Lin and Youde, who encouraged and supported me in pursuing higher education and have given me endless love.

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## 1. Introduction

Deforestation in the Brazilian Amazon has been the subject of debate for more than 50 years. While many groups (inside and outside government) have called for preservation of the forest based on its value for biodiversity, carbon, and other ecosystem services, some parts of the Brazilian government have persistently pushed agricultural development of the region. For example, the land reform agency of the Brazilian government has established agricultural colonization settlements throughout the Amazon, which by 2013 accounted for more than 16% of all deforestation in the Amazon in just 8% of the land area (Yanai et al. 2017). I study a cluster of settlements in the Ouro Preto do Oeste region of Rondônia in the western Amazon. These are typical settlements, with 50 to 100 hectares of forest allocated to individual farm households, which then clear the forest in order to plant crops and pasture.

The Ouro Preto do Oeste region is located in northwest Brazil on the western end of the "arc of deforestation" that extends across the southern Brazilian Amazon (Figure 1.1). This chapter aims to put this region in context and discuss unique regional factors. As background for the following chapters, in which I investigate the factors that drive deforestation decisions and value of the forests, I present five stylized facts that are widely believed to drive decisions about land use and forest ecosystem services in the Amazon and discuss whether and how they apply to Ouro Preto do Oeste.

## 2. Agrarian Settlements and Land Tenure

While Amazon frontier development has often been characterized as a competition for land tenure, with deforestation serving as a way to claim land, the Ouro Preto do Oeste region developed from agrarian reform settlements, which were established by Brazil's federal government in the 1970s. The agrarian settlement program in the Brazilian Amazon is just one example of government-sponsored rural migration schemes across the tropics. These programs relocate populations to remote regions and encourage the conversion of native vegetation to agriculture (Schneider and Peres 2015; Mullan et al. 2017).

Large-scale migration from southern Brazil to agrarian settlement projects in the Amazon began in 1955 (Schneider and Peres 2015). These state-sponsored projects were organized by the National Institute of Agrarian Colonization and Reform (INCRA). INCRA was responsible for agrarian reform, including redistributing land and securing land rights. In the Amazon, INCRA mostly settled families in public forest. From 1964 to 2006, the agency settled 0.8 million families in the Brazilian Legal Amazon[1] (Pacheco 2009). In addition to traditional settlements, in which settlers receive property titles and independently manage their land, INCRA also creates environmentally distinctive settlements, in which settlers only receive a concession for use of the land and conduct activities with low deforestation impact (Yanai et al. 2017). See Figure 1.2.

Although the goal of agrarian settlement projects is to alleviate poverty and promote socioeconomic development by distributing land to landless people, they have been criticized for uneven rural development, inefficient economic outcomes, and high environmental costs (Smith

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[1] The Brazilian Legal Amazon was created in 1953 to identify the Brazilian political-administrative units in the Amazon region. It includes all seven states of the Northern Region (Acre, Amapá, Amazonas, Pará, Rondônia, Roraima and Tocantins) and the whole state of Mato Grosso, as well as the municipalities of the State of Maranhão located west of meridian 44º W (IBGE, 2010).

1981; Diniz et al. 2013; Mullan et al. 2017). Financially, Brazilian agrarian reform to date is the most expensive modern government-induced land redistribution plan (Schneider and Peres 2015). The long and costly process of land titling, budget constraints, and corruption within INCRA has resulted in a large fraction of landholdings that are not legally registered or remain untitled (Araujo et al. 2009).

In the Ouro Preto do Oeste region, large-scale migration and settlement began in the 1970s, mostly through Integrated Colonization Projects (PICs; Projetos Integrados de Colonização) (Figure 1.3). In PICs, INCRA allocated 100 hectare lots to farm households along a grid of unpaved roads (Fearnside 1986) without taking into account biophysical characteristics or household preferences. Starting from the initial four settlements created by INCRA in 1970, 14 whole or partial settlements were created in the study region. Parts of Urupá and Mirante da Serra were settled in the 1980s and 1990s (Sills and Caviglia-Harris 2009) through Federal Settlement Projects (PAs; Projetos de Assentamento Federal). Both PICs and PAs are forms of traditional settlements, which provide basic government services to settlers and in which the dominant activities are agriculture and cattle ranching (Fearnside 1986; Yanai et al. 2017). Some other settlements were created by invasion and later regularized by INCRA.

Similar to other agrarian settlements, successive waves of migrants to the Ouro Preto do Oeste region were attracted by road building, which creates the typical “fishbone” deforestation pattern. Unlike many other parts of the Amazon, households were provided with secure land titles in the agricultural settlements in the region (Jones et al. 1995). According to a 2000 household survey, all households interviewed held legal title and none reported problems with squatters (Sills and Caviglia-Harris 2009). In the early 1990s, the region was subdivided into four, and later six, municipalities: Ouro Preto do Oeste, Vale do Paraíso, Urupá, Mirante da Serra, Nova União, and Teixeirópolis.

## 3. Soil Quality

Soil quality is a key factor in agricultural production decisions, and thus is one of the biophysical characteristics that may influence deforestation (Fearnside 1984; Pfaff 1999; Andersen et al. 2002). Soil types and capacity for agricultural production vary across the Amazon (Cerri et al., 2004). However, the literature has long described Amazonian soils as generally nutrient-poor and not capable of sustaining agricultural production sufficiently without substantial chemical inputs (Hecht 1993). Rapid degradation of soil quality after conversion of forest to agricultural land has been described as a vicious cycle or “hollow frontier”: farmers abandon degraded land and deforest more by slashing and burning, which results in further land degradation (Witcover et al. 2006; Styger et al. 2007).

By overlaying agrarian settlements on a soil-fertility index, Figure 1.4 shows that although there is substantial variation in soil quality across agrarian settlements in the Legal Amazon, most agrarian settlements were established on relatively nutrient-rich soils. The Ouro Preto do Oeste region has one of the highest soil fertility indices, indicating that it is one of the most appropriate places for agriculture production. These relatively fertile soils were a motivation for continued migration to the Ouro Preto do Oeste region in the 1980s.

## 4. Agricultural Production

The majority of deforestation is due to conversion of forest to cattle pastures (Barona et al. 2010). There are slaughterhouses for beef cattle throughout the Amazon, and beef production is considered both by scientists (McAlpine et al. 2009) and by activists (Greenpeace 2009) to be a key driver of deforestation. Pasture and mixed crop and pasture are the dominant types of agricultural land use in the Brazilian Legal Amazon, which are distributed in the northeast and southwest; crop lands are distributed throughout the southern Legal Amazon (Sparovek et al. 2012).

In our study region, on average, 20.1% of the land on a property was pasture in 1986, increasing to 77.6% in 2009. Creating pasture has been the immediate motivation for most deforestation in the study region. According to the 2010 census, 40% of the Brazilian cattle herd is in the Brazilian Legal Amazon. The state of Rondônia accounts for less than 5% of the land area of the Brazilian Legal Amazon, but 17% of its cattle herd, and the Ouro Preto do Oeste region accounts for less than 3% of the state's land area but 11% of its cattle herd (Figure 1.5). Comparing across years, the size of the cattle herd in the Ouro Preto do Oeste region increased 344% between 1991 and 2010.

Unlike the rest of the Amazon, most of the cattle herd in Ouro Preto do Oeste is for diary production. The Amazon accounts for only 3.9% of the total Brazilian dairy herd, and 8.7% of Brazilian milk production. However, Rondônia specializes in dairy production, with 35% of the dairy cattle and 32% of the milk production in the Amazon. Ouro Preto do Oeste has 31% of the dairy herd and produces 37% of the milk in the state. The head of dairy cattle and liters of milk produced in the Ouro Preto do Oeste region grew 416% and 590%, respectively, between 1991 and 2010.

Median milk productivity in the Brazilian Amazon (689 liters/cow/year) is lower than the median for the rest of Brazil (1,224 liter/cow/year) (IBGE 2015), and far behind other developed countries, such as New Zealand (3,500-4,200 liter/cow/year) (LIC and DairyNZ 2014) and the

European Union (4,000-8,000 liter/cow/year) (Eurostat 2014; Zu Ermgassen et al. 2017). However, milk productivity in the Ouro Preto do Oeste region (1,141.2 liter/cow/year) is close to the national median. The stocking rate of dairy cattle in the Ouro Preto do Oeste region (0.44 cow/hectare) is also higher than the average level of the Brazilian Amazon (0.1 cow/hectare). Costa et al. (2018) defines a dairy milk productivity index with productive and socioeconomic indicators and classifies milk productivity for Brazilian municipalities into four clusters (high, medium, low, and no milk productivity). The Ouro Preto do Oeste region is in the cluster of high milk productivity.

While milk productivity in the Ouro Preto do Oeste region differs from the rest of the Amazon, other characteristics for dairy production in the region are similar: (1) Dairy farming is mainly managed by small households, whose farm size ranges from 20 to 400 hectares; (2) milk production is for self-subsistence or local markets; and (3) family labor is the major input, and chemical input is scarce (Zu Ermgassen et al. 2017).

Milk prices in the Ouro Preto do Oeste region are generally lower than the country-level price, but similar to the state-level price over time (Panel A, Figure 1.6). In 2010 the average milk price in the Ouro Preto do Oeste region was 0.55 R$/liter, which is 20% less than the country-level. Comparing among the six municipalities in the Ouro Preto do Oeste region and two cities immediately outside the region, little variation is found in terms of either the level or time trend in the price of milk (Panel B, Figure 1.6).

## 5. Urban Development

People often visualize the Amazon as a jungle. However, the Amazon has experienced accelerated urbanization since 1980 (Browder and Godfrey 1997); by 2010, 71.5% of the

Brazilian Amazonia population lived in urban areas (Tritsch and Le Tourneau 2016). Between 1970 and 2010, the urban population in the Brazilian Legal Amazon increased by 430%, while in the rest of Brazil the urban population increased by 204% (IBGE 2010). In the Ouro Preto do Oeste region, the urban population accounted for 54% of the total population in 2010, while in 1991 it only accounted for 29% of the total. Comparing among municipalities in the region, regional heterogeneities in the proportion of urban population exist (Figure 1.7). While the central municipality of Ouro Preto do Oeste has a mostly urban population (74%; IBGE 2010), the other five municipalities were still predominantly rural in 2010. An increasing trend of rural population is observed in all of the six municipalities.

The extent and meaning of urbanization cannot be demonstrated simply by documenting the growth of the urban population (Becker 2005). Another way to demonstrate contemporary urban development is to use the amount of nighttime light observed from outer space (Mellander et al. 2015). Nighttime light has been used to measure economic activities, growth in the population, and urbanization (Amaral et al. 2006; Montgomery 2008; Huang et al. 2014). Differences in nighttime light among urban centers may reflect differences in population growth, wage growth, and stages of urbanization (Huang et al. 2014). These satellite-based time series data, which are available from the Defense Meteorological Satellite Program–Operational Linescan System (DMSP-OLS), were collected by nighttime light raters from 1992 to 2013. According to data for nighttime light in the Brazilian Amazon, most agrarian settlements experienced urban transformation (Figure 1.8). In and around Ouro Preto do Oeste, there are three cities—Jaru, Ouro Preto do Oeste, and Ji-Paraná, which clearly have had the highest light intensity and largest extent of light since 1992 (Figure 1.9). In 1992, in addition to the three cities, only Mirante da Serra and Urupá were lighted. In 1993, Teixeirópolis and Nova União started to be lighted at lower intensity, and light intensity in Mirante da Serra increased substantially. Vale do Paraíso was dark until the end of 1993. In later years, up to 2010, all municipalities experienced increasing light intensity as well as expanding light area, but at different growth rates. In addition to the three cities, Vale do Paraíso and Rondominas in the northeast and Mirante da Serra and Urupá in the southeast grew rapidly and had higher light intensity. The lowest light intensity was in Teixeirópolis.

## 6. Water Availability

Another long-standing image of the Amazon rainforest is that it is humid and has abundant sources of water. However, except for the northwest and a small part of the northeast, most of the Brazilian Amazon experiences a distinct dry season. The Ouro Preto do Oeste region's climate is classified as tropical monsoon (Figure 1.10), with an average temperature of 24℃, annual precipitation of 2,300 mm, and a dry season from June to September (rainfall in the driest month is less than 60 mm; Alvares et al. 2013).

In addition to the limited precipitation in the dry season, there is evidence that rainfall has declined in the northern Amazon, and dry events in the southern Amazon have been increasing since 1970 (Malhi et al. 2008, 2009). A widespread, once-in-a-century drought in 2005 was followed by a more severe drought in 2010 (Marengo et al. 2011; Xu et al. 2011). The western and southern parts of the Amazon suffered the most severe drought in 2005, with rivers and lakes at the lowest water levels ever observed (Zeng et al. 2008).

In general, the Ouro Preto do Oeste region is typical of agrarian settlements and is well within the range of variation across the Brazilian Amazon. However, it does not fit many widely held assumptions. Farm households in my study region were provided with secure land titles and allocated to relatively nutrient-rich soils. The dairy industry is the dominant agricultural activity, and milk is the main commercial product of nearly all farm families. Contrary to long-standing images of the Amazon rainforest, the study region has experienced accelerated urbanization, a distinct dry season, and severe drought years.

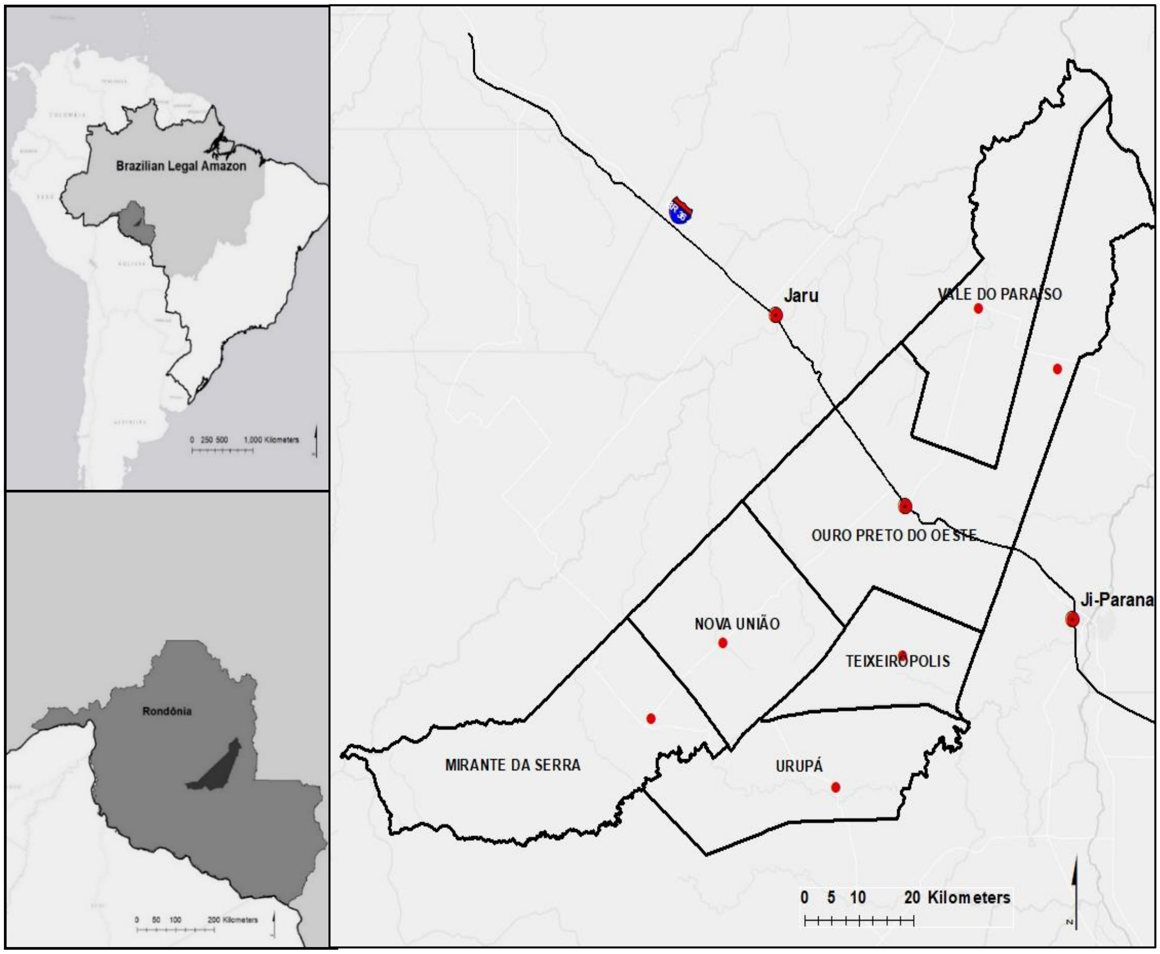

Figure 1.1. Study Area

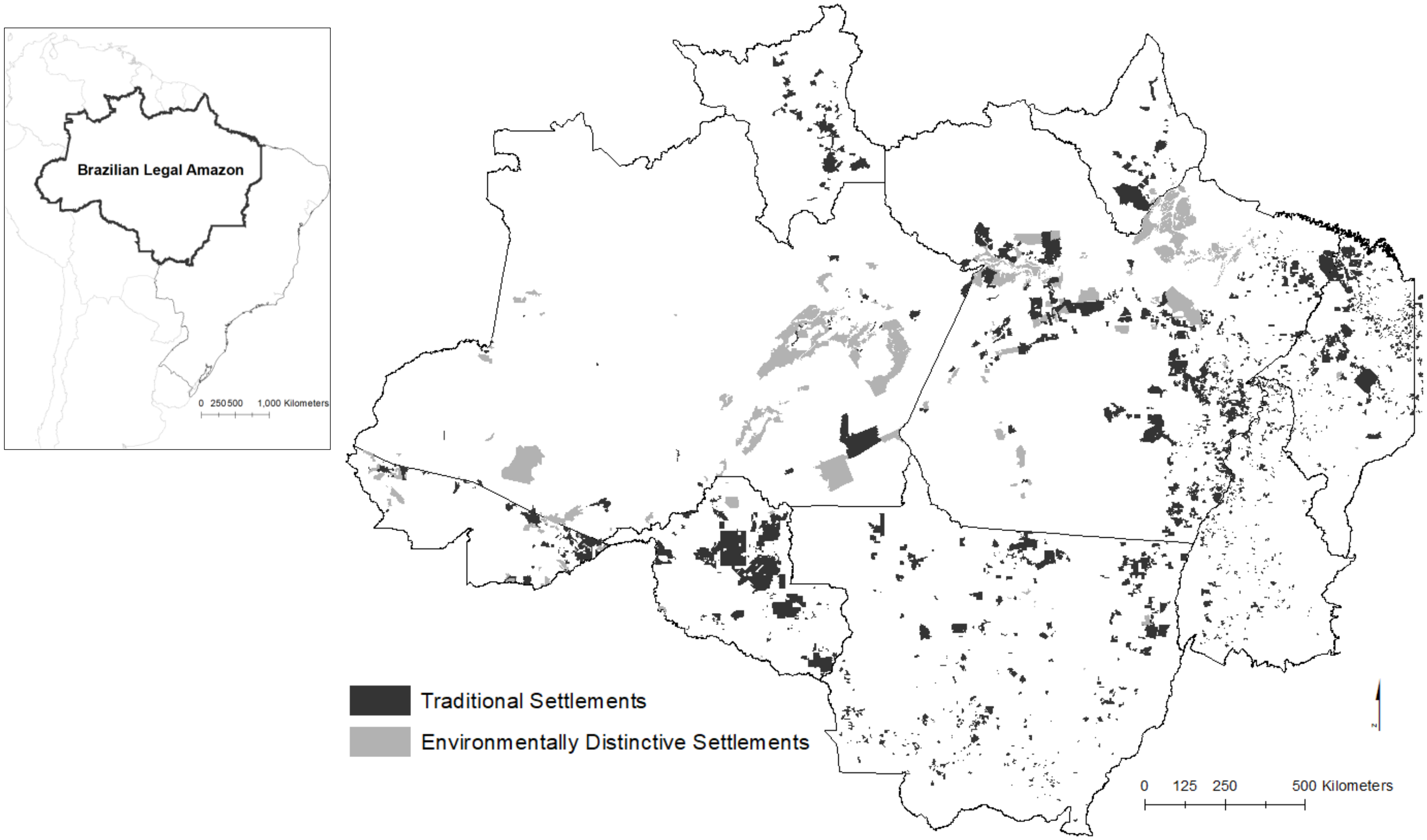

Figure 1.2. Two Types of Agrarian Settlements in the Brazilian Legal Amazon

*Notes:* Traditional settlements include Federal Settlement Projects (PAs), Integrated Colonization Projects (PICs), Directed Settlement Projects (PADs), and other settlements except for Environmentally Distinctive Settlements. Environmentally Distinctive Settlements include Agro-Extractivist Settlement Projects (PAEs), Sustainable Development Projects (PDSs), and Forest Settlement Projects (PAFs).
*Data source:* INCRA 2018; IMAZON 2018;

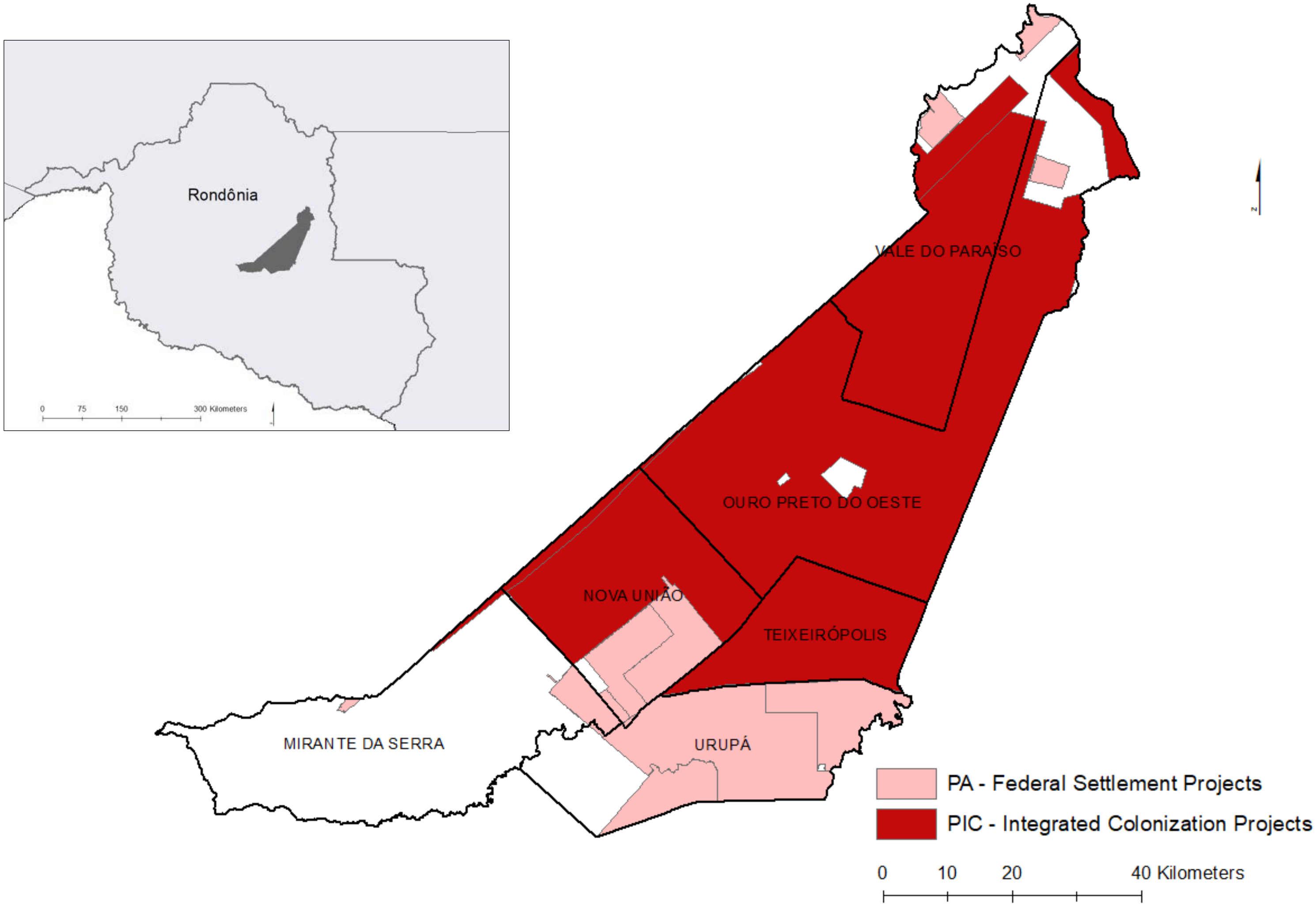

Figure 1.3. Agrarian Settlements in the Ouro Preto do Oeste Region

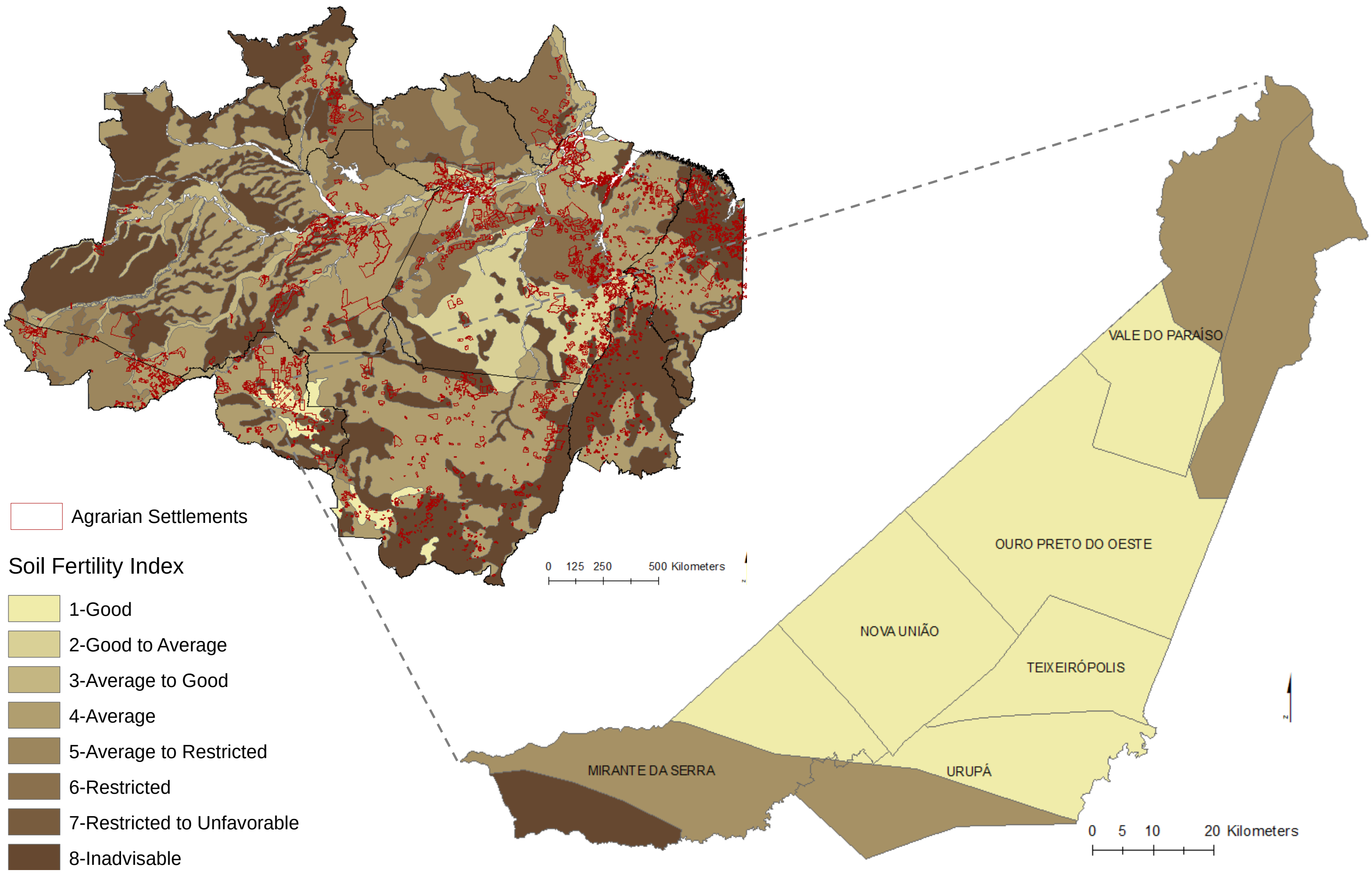

Figure 1.4. Soil Fertility in the Ouro Preto do Oeste Region

*Data Source*: IBGE 2010

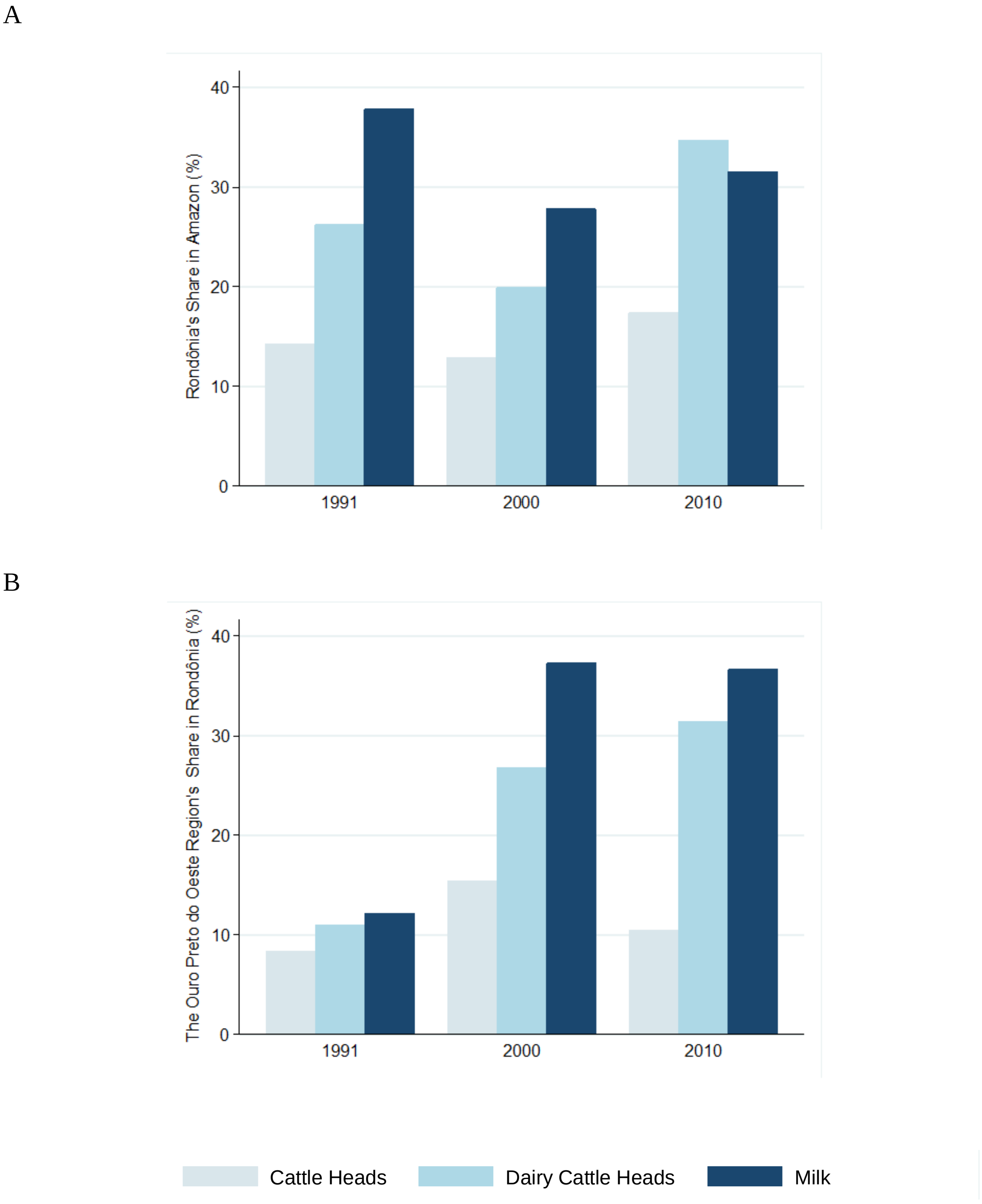

Figure 1.5. State and Region’s Shares of Cattle and Dairy Production

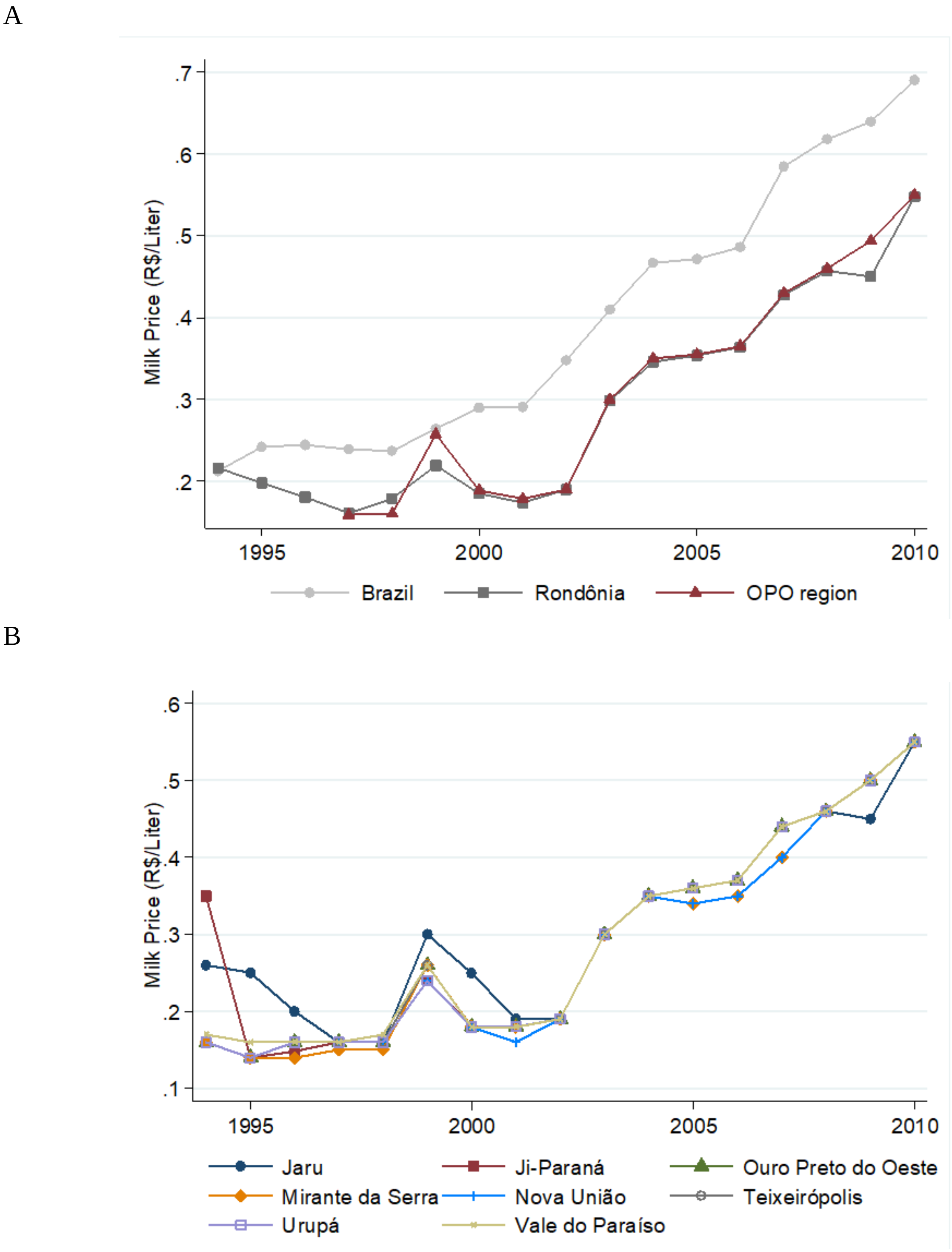

Figure 1.6. Milk Price Change Over Time and Space

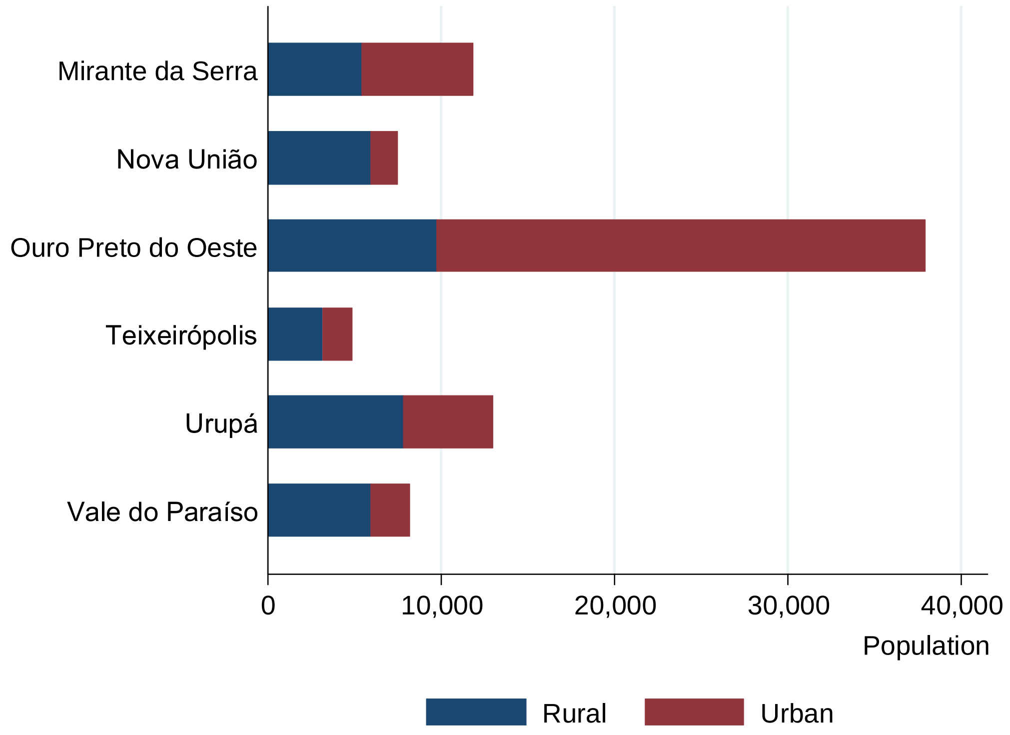

Figure 1.7. Urban and Rural Population in the Ouro Preto do Oeste Region

*Data Source*: IBGE 2010

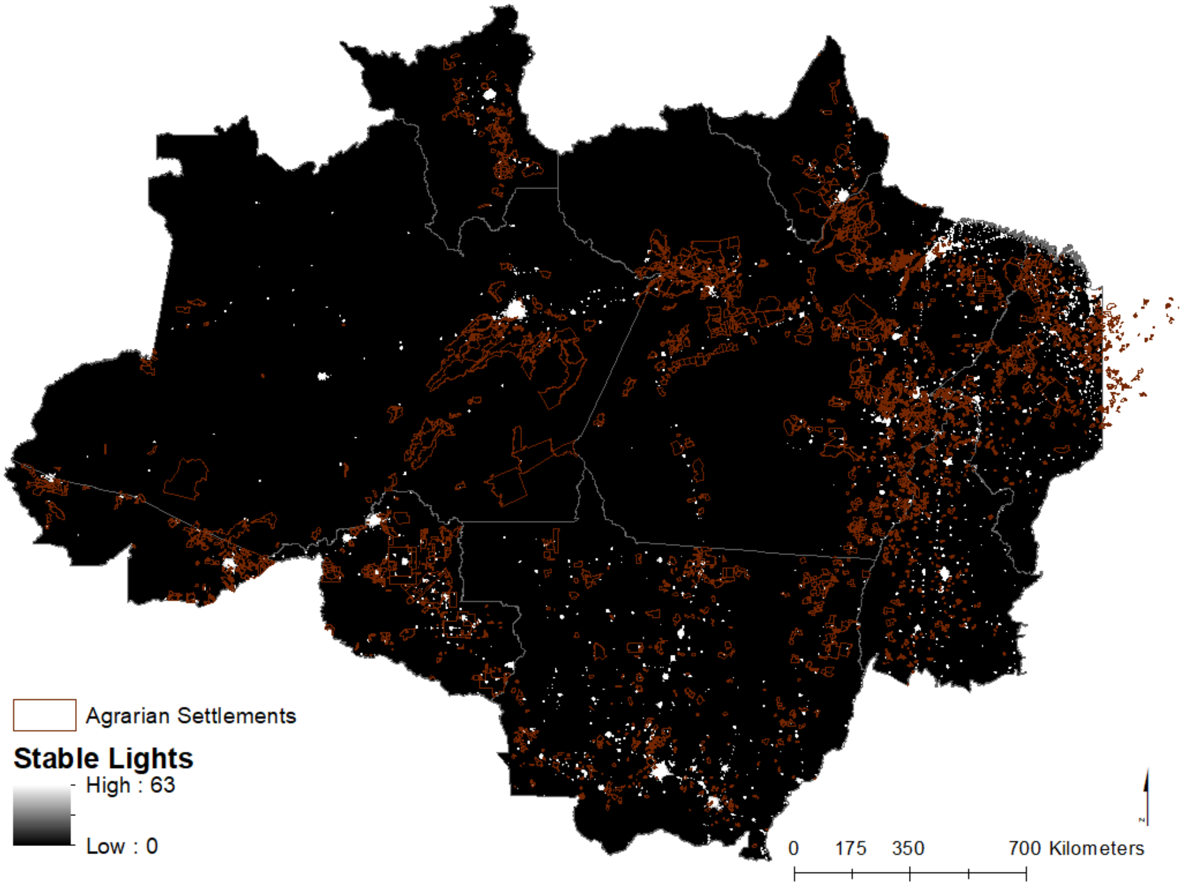

Figure 1.8. Nighttime Lights in the Brazilian Legal Amazon, 2013

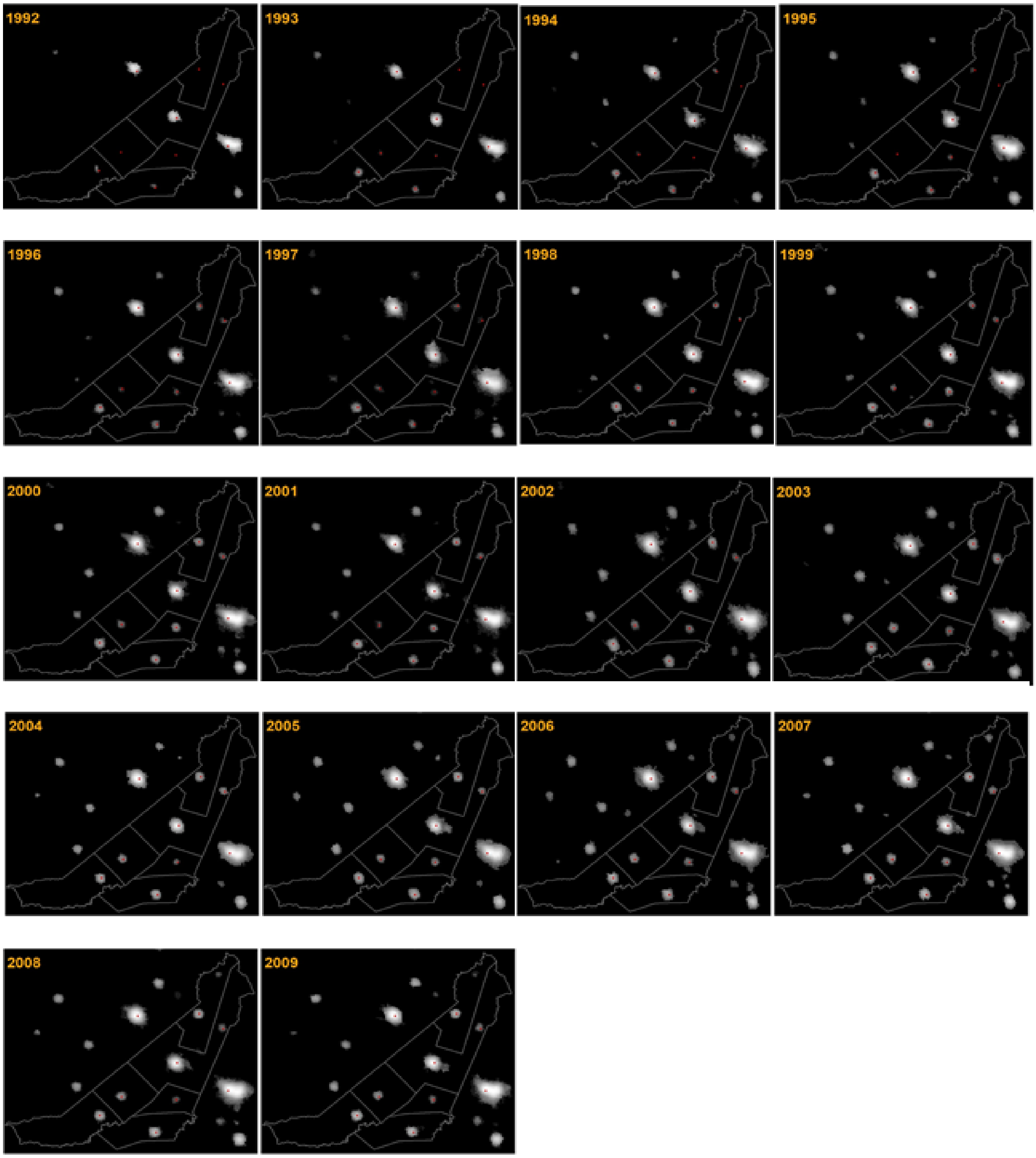

Figure 1.9. Nighttime Lights in the Ouro Preto do Oeste Region, 1992-2009

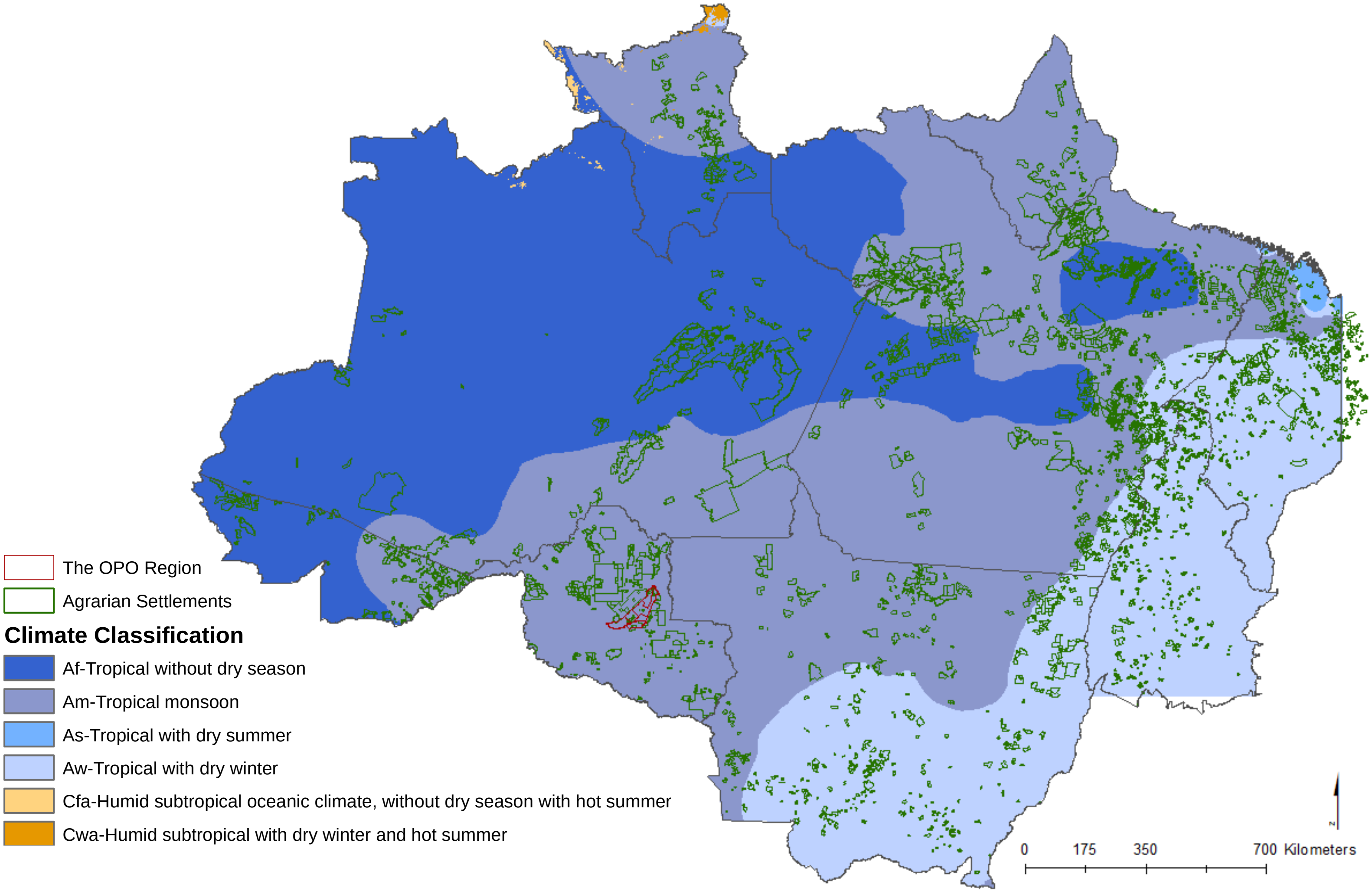

Figure 1.10. Climate classification for the Agrarian Settlements in the Brazilian Amazon

*Data Source*: Alvares et al. 2013

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# CHAPTER 2: THE EVOLVING RELATIONSHIP BETWEEN MARKET ACCESS AND DEFORESTATION ON THE AMAZON FRONTIER

## 1. Introduction

Deforestation of the Amazon forest is occurring mainly in Brazil, where about 62% of the forest is located, and about 80% of deforestation has taken place (Hansen et al. 2013). From 1988 to 2004, Brazil had the world's highest rate of deforestation, averaging 18,400 km$^2$ per year (INPE 2017). After a peak in 2004, Brazil also had the largest reduction in deforestation (and carbon emissions) of any country through 2012; then rates again increased to 7,893 km$^2$ in 2016 (INPE 2017). Partly because of growing concerns over carbon emissions from tropical deforestation, there were government efforts to reduce deforestation in the Brazilian Amazon in the 2000s. Yet questions remain about whether these efforts caused the reduction in deforestation and, if so, which interventions were most effective. One challenge for evaluating previous policies and crafting the best policy response for the future is that decision-making and the drivers of deforestation change over time as the frontier evolves.

A large body of research has examined the drivers of deforestation and land-use decisions in the Amazon. The standard theoretical framework posits that the probability of deforestation in any given location is a function of its biophysical characteristics (Ricardian theory) and market access (Von Thünen theory) (Pfaff et al. 2013). Von Thünen theory relates land rents to transportation costs and to the costs of establishing land tenure (Von Thünen 1966; Angelsen 2007). In the context of the Amazon, this theory has been put forth to explain observed patterns of deforestation through two channels: a higher price for agricultural outputs (at the farmgate) increases the derived demand for agricultural land (which is obtained by clearing forest), and higher profitability encourages investment in protecting land tenure, including through deforestation (Schneider 1993).

The empirical literature has generally used location as a proxy for farm-gate price, and has represented market access as Euclidean distance to the nearest paved road or urban center (Sills 2014). Many previous studies have found a negative relationship between this distance and deforestation (Chomitz and Gray 1996; Geoghegan et al. 2004; De Souza Soler et al. 2010; Caviglia-Harris and Harris 2011). This result is consistent with the Von Thünen theory of land rent, which suggests that the rents to agricultural lands are highest closest to markets (Sills and Caviglia-Harris 2009), thus creating an incentive to clear those lands first. Some studies have used improved proxies for market access—for example, road distance to markets over the relevant transportation network (Aguiar et al. 2007; Mann et al. 2010).

The negative effect of distance to an urban center on deforestation has typically been interpreted as demonstrating the expected relationship between the farm-gate prices of outputs and the derived demand for agricultural land. However, access to urban centers may have multiple and contradictory influences on household decisions. As explored in the regional economics and rural development literature, researchers are recognizing new and growing connections between urban and rural space in the Amazon (Browder and Godfrey 1997; Simmons et al. 2002; Padoch et al. 2008). For example, proximity to urban centers could mean better off-farm employment opportunities, and therefore a higher opportunity cost for household labor used in deforestation or agriculture. Proximity to an urban center also means that environmental enforcement agents based in those cities have better access to the farm.

This paper incorporates these multiple dimensions of urban access into a household production framework, and shows that their combined effect on deforestation is ambiguous and could change over time. We examine the evolution by modeling deforestation from 1992 to 2009 on 8,770 farm properties typical of the agrarian reform settlements that have been established by the federal agency, the National Institute for Colonization and Agrarian Reform (INCRA), throughout the Amazon. To the best of our knowledge, this is the first study that analyzes the long-term evolution of deforestation at the property level in the Amazon. We test for structural shifts in the effect of urban access on deforestation in these agrarian reform settlements. We also conduct three robustness checks on the effects of forest stock, the mechanism of farm gate price, and other specifications on market access. In our study region, land tenure is generally secure, which brings into sharper focus the role of prices (for outputs and labor) and enforcement as possible reasons why distance to urban center might be important.

## 2. Theoretical Framework

To place market access in the context of other drivers of deforestation and identify its possible roles in decisions about deforestation, this section presents a household production model. Farm households in agricultural settlements in the Brazilian Amazon are integrated production and consumption units that rely primarily on their own labor for production and consume at least some portion of their farm production. In this setting, the household production model is an appropriate framework for understanding integrated household decisions about production, consumption, and labor supply (Sadoulet and de Janvry 1995; Singh et al. 1986). We do not aim to set up a universal model of deforestation, but rather a model that is appropriate to agricultural settlements, in which each settler household is allocated a given area of forest they can put into agricultural production by allocating labor to deforestation.

We start with an intertemporal model of unitary decision-making. This is because deforestation is a fundamentally intertemporal process, with forest cleared in the present to obtain agricultural land for use in multiple future periods. We assume unitary household decision-making, because the data available to estimate the model are from household surveys that make the same assumption. Thus, “household” decision-making refers either to the choices of the head of household (typically a man) or some other process of collective decision-making within the household that we do not explicitly model. Assuming the household cares about utility over an infinite time horizon (because he cares about future generations), he maximizes the utility from consumption of self-produced agricultural goods $C_t^A$, market goods $C_t^M$, and leisure $T_t^l$ over time, conditioned on household characteristics $z_t^C$ that influence preferences, and subject to a set of constraints: the production function, time (labor) constraint, accumulation of agricultural land, land constraint, and budget constraint[2]:

$$\max_{C_t^A, C_t^M, T_t^A, T_t^D, T_t^O, I_t^A} E_t \sum_{t=1}^{\infty} \beta^t U\left(C_t^A, C_t^M, T_t^l; z_t^C\right) \tag{1}$$

s.t.

$$Q_t^A = Q(T_t^A, L_t^A, I_t^A; z_t^L) \tag{2}$$

$$T_t = T_t^A + T_t^D + T_t^O + T_t^l \tag{3}$$

$$L_t^A = L_{t-1}^A + D_t \tag{4}$$

$$L_t^A \leq \overline{L} \tag{5}$$

$$(P_t^A - x_t^A)C_t^A + (P_t^M + x_t^M)C_t^M + f_t\left[\frac{L_t^A}{\overline{L}} - (1 - r_t)\right]$$

$$= \left[(P_t^A - x_t^A)Q_t^A - (P_t^I + x_t^I)I_t^A\right] + (W_t^O - x_t^O)T_t^O + S_t \tag{6}$$

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[2] We omit the subscript i for household in the presentation of the model.

Equation (2) represents the production function of agriculture good $Q_t^A$ in period *t*, which is a function of the household's time (labor) devoted to agriculture production $T_t^A$, the area of land in agricultural production $L_t^A$, and other purchased inputs $I_t^A$[3], conditioned on land characteristics $z_t^L$. Time devoted to agricultural production $T_t^A$ in period *t* is limited by the household time constraint, equation (3). In addition to agricultural production, the household allocates its total amount of time $T_t$ to deforestation $T_t^D$, off-farm work $T_t^O$, and leisure $T_t^l$.

The accumulation of agricultural land is illustrated by equation (4). We treat the process of agricultural land accumulation as the evolution of capital, and deforestation is the investment. The area of land devoted to agriculture in the current period, $L_t^A$, is derived from the old agricultural land in the last period, $L_{t-1}^A$, plus agricultural land newly created through deforestation in the current period, $D_t$ (Pendleton and Howe 2002). Deforestation is a labor-intensive process (Vosti et al. 2002) and is a function of labor allocated to deforestation:

$$D_t = g(T_t^D) \tag{7}$$

Substituting (7) into (4), we have:

$$L_t^A = L_{t-1}^A + g(T_t^D) \tag{8}$$

From another point of view, we can rewrite the accumulation of agricultural land as:

$$L_t^A = L_0^A + D_{t-(t-1)} + \cdots + D_{t-1} + D_t \tag{9}$$

By rearranging the equation (9) we have that the current period deforestation $D_t$ is equal to the current agricultural land minus the sum of the initial area of agricultural land and the cumulative deforestation areas till the last period:

$$D_t = L_t^A - (L_0^A + \sum_{i=1}^{t-1} D_{t-i}) \tag{10}$$

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[3] The hired labor on the farm is included in other purchased inputs $I_t^A$.

Equation (5) represents the land constraint. Given that land tenure in our empirical case is secure and total land size is fixed for each household, neither the area of agricultural land nor the area of deforestation can exceed the exogenously given property size $\overline{L}$. Also, deforestation is non-negative, since it measures the net loss of primary forest (old-growth forest) in our study. The non-negative deforestation also reflects the predominant pattern in our study region, where there has been relatively little re-growth of forest and almost no forest plantations.

Beyond the land constraint, deforestation is limited by policy enforcement[4]. To reflect this, we incorporate the possibility of a fine [5]for deforestation that exceeds the legal limit for each property. Specifically, we focus on the Brazilian Forest Code's requirement that forest land owners retain a minimum percentage of their land in a "legal reserve" of forest. For each percent of land used for agriculture beyond the legal maximum $(1 - r_t)$, where $r_t$ is the legal reserve requirement or percentage of property that must be conserved as forest in the period *t*, the household risks being fined for breaking the law and illegally clearing forest. Let $f_t$ represent the expected monetary amount of the fine in period *t* (i.e., the fine for excess deforestation multiplied by the household's expected probability of being fined), which is the shadow cost of expanding agriculture land beyond the legal amount allowed (Assunção et al. 2015). Therefore, the expected expense associated with illegal deforestation is equal to $f_t[\frac{L_t^A}{\overline{L}} - (1 - r_t)]$, which is

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[4] The Brazilian Forest Code (law) has required landowners to maintain 20% to 80% of their rural properties under native vegetation in different time periods and different regions (Soares-Filho et al. 2014). The first Forest Code (Federal Decree No. 23793) was created and passed in 1934 and requires that 25% of the property be conserved with forest as a legal Reserve (LR). Conservation requirements for LRs and the stringency of enforcement changed over our study period. The Forest Code also requires that landowners retain forest in riparian buffers, but those typically represent only a small fraction of the total property and we therefore do not include in our model of landowner decisions.

[5] The penalties for excessive deforestation now include confiscation of assets and restricted access to credit and commercialization channels, but historically monetary fines were imposed although they were rarely paid (Börner et al. 2015). After 2004, under improved monitoring for enforcement, fines were issued with satellite images showing the property boundaries and existing deforestation (Fearnside 2005). Under the mechanism of the Environmental Reserve Quota (CRA, Portuguese acronym) introduced nationally in 2012, landowners are required to georeference their property boundaries and remaining forests, and failure to do so will result in loss of access to credit and output markets (Azevedo et al. 2017).

included in budget constraint equation (6). While there is an emerging market for forest conservation credits (Soares-Filho et al. 2016), there was no benefit for maintaining excess legal reserve in Rondônia during our study period. Thus, $f_t = 0$ when $[\frac{L_t^A}{L} - (1 - r_t)] \leq 0$ .

In budget constraint equation (6), the household's total expenses equal its total income in period *t*. In addition to any fines for expanding agricultural land beyond legal limits $f_t[\frac{L_t^A}{L} - (1 - r_t)]$, the household uses its income to consume self-produced agricultural goods $C_t^A$ and other market goods $C_t^M$. The sales price received by a household for any agricultural goods not consumed (the farm-gate price) equals the market price of the agricultural goods $P_t^A$ minus a transaction cost $x_t^A$; and the purchase price of other market goods equals the market price of the market goods $P_t^M$ plus a transaction cost $x_t^M$ incurred in buying (Sadoulet and de Janvry 1995; Key, Sadoulet, and de Janvry 2000). While transaction costs include all costs of measuring what is being exchanged and enforcing agreements (North 1994), costs associated with distance to market are among the most substantial in the agricultural settlements in the Amazon. These include not only the cost of transporting goods and people, but also potentially fewer market players (which enables intermediaries to capture higher margins) and less information available (which leads to higher search and recruitment costs; Sadoulet and de Janvry 1995) farther from a market. The major household income source is agricultural product sales. The household sells $Q_t^A$ amount of agricultural products at the farm-gate price $(P_t^A - x_t^A)$, coincident with the expenses of purchased inputs[6] $(P_t^I + x_t^I)I_t^A$. The household could also earn income from off-farm jobs, either on other farms or in urban centers. In the case of employment in urban centers, the

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[6] The coincident costs of agricultural production also include own labor on agricultural production and on deforestation. However, wage payments and earning for own labor would cancel out in the budget constraint, and thus for simplicity, we only include the cost of purchased inputs (including hired labor) in the equation.

household bears the transaction costs of traveling to work, and the take-home wage is $(W_t^O - x_t^O)$. The household also may earn exogenous transfers $S_t$ (e.g., government welfare payments).

Given (8) and (2), the budget constraint (6) can be rewritten as:

$$(P_t^A - x_t^A)C_t^A + (P_t^M + x_t^M)C_t^M + f_t\left[\frac{[L_{t-1}^A + g(T_t^D)]}{\overline{L}} - (1 - r_t)\right]$$
$$= [(P_t^A - x_t^A)Q(T_t^A, T_t^H, (L_{t-1}^A + g(T_t^D)); z_t^L) - (P_t^I + x_t^I)I_t^A] + (W_t^O - x_t^O)T_t^O + S_t \tag{11}$$

The Lagrangian of this household utility maximization problem can be written as:

$$\mathcal{L} = E_t \sum_{t=1}^{\infty} \beta^t U\left(C_t^A, C_t^M, T_t^l; z_t^C\right)$$
$$+ \sum_{t=1}^{\infty} \beta^t \lambda_t \Big\{\left[(P_t^A - x_t^A)Q\left(T_t^A, I_t^A, \left(L_{t-1}^A + g(T_t^D)\right); z_t^L\right) - (P_t^I + x_t^I)I_t^A\right] + (W_t^O - x_t^O)T_t^O$$
$$+ S_t - (P_t^A - x_t^A)C_t^A - (P_t^M + x_t^M)C_t^M - f_t\left[\frac{[L_{t-1}^A + g(T_t^D)]}{\overline{L}} - (1 - r_t)\right]\Big\}$$
$$+ \sum_{t=1}^{\infty} \beta^t \varphi_t\left(T_t - T_t^A - T_t^D - T_t^O - T_t^l\right) + \sum_{t=1}^{\infty} \beta^t \mu_t \left[\overline{L} - L_{t-1}^A - g(T_t^D)\right] \tag{12}$$

where $\lambda_t$, $\varphi_t$ and $\mu_t$ are the Lagrange multipliers associated with the budget constraint, the labor constraint, and the land constraint. The first order conditions with respect to the choice variables:

$$\frac{\partial \mathcal{L}}{\partial C_t^A} = \frac{\partial U}{\partial C_t^A} - \lambda_t(P_t^A - x_t^A) = 0 \tag{13}$$

$$\frac{\partial \mathcal{L}}{\partial C_t^M} = \frac{\partial U}{\partial C_t^M} - \lambda_t(P_t^M + x_t^M) = 0 \tag{14}$$

$$\frac{\partial \mathcal{L}}{\partial T_t^A} = \lambda_t(P_t^A - x_t^A)\frac{\partial Q_t^A}{\partial T_t^A} - \varphi_t = 0 \tag{15}$$

$$\frac{\partial \mathcal{L}}{\partial T_t^D} = \lambda_t \left[ (P_t^A - x_t^A) \frac{\partial Q_t^A}{\partial D_t} \frac{\partial g(T_t^D)}{\partial T_t^D} - \frac{f_t}{\overline{L}} \frac{\partial g(T_t^D)}{\partial T_t^D} \right] - \varphi_t - \mu_t \frac{\partial g(T_t^D)}{\partial T_t^D}$$

$$+\beta E_t \left\{ \lambda_{t+1} \left[ (P_{t+1}^A - x_{t+1}^A) \frac{\partial Q_{t+1}^A}{\partial D_t} \frac{\partial g(T_t^D)}{\partial T_t^D} - \frac{f_{t+1}}{\overline{L}} \frac{\partial g(T_t^D)}{\partial T_t^D} \right] - \mu_{t+1} \frac{\partial g(T_t^D)}{\partial T_t^D} \right\} = 0 \qquad (16)$$

$$\frac{\partial \mathcal{L}}{\partial T_t^O} = \lambda_t (W_t^O - x_t^O) - \varphi_t = 0 \qquad (17)$$

$$\frac{\partial \mathcal{L}}{\partial I_t^A} = \lambda_t \left[ (P_t^A - x_t^A) \frac{\partial Q_t^A}{\partial I_t^A} - (P_t^I + x_t^I) \right] = 0 \qquad (18)$$

The complementary slackness condition:

$$\mu_t^* [\overline{L} - L_{t-1}^A - g(T_t^D)] = 0 \qquad (19)$$

$$\mu_t^* \geq 0 \qquad (20)$$

The initial condition: $L_0^A$ is given. (21)

A utility-maximizing household will continue allocating labor to deforestation up to the point where the marginal returns to labor in deforestation are equal to the marginal returns to labor in agricultural production and off-farm work:

$$\lambda_t \left[ (P_t^A - x_t^A) \frac{\partial Q_t^A}{\partial D_t} \frac{\partial g(T_t^D)}{\partial T_t^D} - \frac{f_t}{\overline{L}} \frac{\partial g(T_t^D)}{\partial T_t^D} \right] - \mu_t \frac{\partial g(T_t^D)}{\partial T_t^D}$$

$$+\beta E_t \left\{ \lambda_{t+1} \left[ (P_{t+1}^A - x_{t+1}^A) \frac{\partial Q_{t+1}^A}{\partial D_t} \frac{\partial g(T_t^D)}{\partial T_t^D} - \frac{f_{t+1}}{\overline{L}} \frac{\partial g(T_t^D)}{\partial T_t^D} \right] - \mu_{t+1} \frac{\partial g(T_t^D)}{\partial T_t^D} \right\}$$

$$= \lambda_t (P_t^A - x_t^A) \frac{\partial Q_t^A}{\partial T_t^A} = \lambda_t (W_t^O - x_t^O) \qquad (22)$$

From the first order condition with respect to the consumption of agricultural goods (13) and the consumption of other market goods (14), $\lambda_t$ can be interpreted as the marginal utility of consumption. The first order condition with respect to labor in deforestation, equation (16), shows the evolution of goods consumption along an optimal path. $\mu_t$ is the shadow price for land evolution, equation (4). Substituting (13) and (17) into (16), and rewriting (16) yields the marginal agricultural output of deforestation in the period *t*:

$$\frac{\partial Q_t^A}{\partial D_t} = \frac{1}{\frac{\partial U}{\partial C_t^A}} \left\{ \left[ \frac{\frac{\partial U}{\partial C_t^A} f_t}{\overline{L}(P_t^A - x_t^A)} + \mu_t \right] + \beta E_t \left[ \frac{\frac{\partial U}{\partial C_{t+1}^A} f_{t+1}}{\overline{L}(P_{t+1}^A - x_{t+1}^A)} + \mu_{t+1} - \frac{\partial Q_{t+1}^A}{\partial D_t} \frac{\partial U}{\partial C_{t+1}^A} \right] + \frac{\frac{\partial U}{\partial C_t^A}(W_t^O - x_t^O)}{\frac{\partial g(T_t^D)}{\partial T_t^D}(P_t^A - x_t^A)} \right\} \tag{23}$$

Following Von Thünen's theory, the transaction cost is dominated by transportation cost and is assumed to be a function of distance to an urban center (Chomitz and Gray 1996). Holding everything else constant, an increase in distance will decrease the farm-gate price of agricultural products and decrease the take-home wage for off-farm work:

$$P_t^A - x_t^A = p_t^A(d) \tag{24}$$

$$W_t^O - x_t^O = p_t^O(d) \tag{25}$$

where $\frac{\partial p_t^A(d)}{\partial d} < 0$, and $\frac{\partial p_t^O(d)}{\partial d} < 0$.

Furthermore, the policy stringency parameter or shadow cost of illegal deforestation, $f_t$, can also be written as a function of distance. Because law enforcement personnel are typically based in urban centers and often face transportation constraints, landowners may expect a higher risk of being caught for illegal clearing or burning if their land is closer to an urban center. This suggests that the shadow cost of illegal deforestation $f_t$ is negatively related to the distance:

$$f_t = p_t^f(d) \tag{26}$$

where $\frac{\partial p_t^f(d)}{\partial d} < 0$.

Substituting (24-26) into (23), we have:

$$\frac{\partial Q_t^A}{\partial D_t} = \frac{1}{\frac{\partial U}{\partial C_t^A}} \left\{ \left[ \frac{\frac{\partial U}{\partial C_t^A}}{\overline{L}} \frac{p_t^f(d)}{p_t^A(d)} + \mu_t \right] + \beta E_t \left[ \frac{\frac{\partial U}{\partial C_{t+1}^A}}{\overline{L}} \frac{p_{t+1}^f(d)}{p_{t+1}^A(d)} + \mu_{t+1} - \frac{\partial Q_{t+1}^A}{\partial D_t} \frac{\partial U}{\partial C_{t+1}^A} \right] + \frac{\frac{\partial U}{\partial C_t^A}}{\frac{\partial g(T_t^D)}{\partial T_t^D}} \frac{p_t^O(d)}{p_t^A(d)} \right\} \tag{27}$$

Equation (27) incorporates the multiple dimensions of distance to an urban center and reveals their different effects on the agricultural land expansion (deforestation) decision. We assume that additional agricultural land converted from forest increases agricultural production at a decreasing rate, reflecting the empirical regularity of the inverse productivity relationship (Pendleton and Howe 2002; Assunção et al. 2007); that is, $\frac{\partial Q_t^A}{\partial D_t} > 0, \frac{\partial^2 Q_t^A}{\partial^2 D_t} < 0$. So, a higher marginal agricultural output of deforestation implies less deforestation. Holding all things equal, an increase in distance to an urban center decreases the shadow cost of illegal deforestation and, at the same time, the farm-gate price of agricultural goods. Therefore, the change in the ratio $\frac{p_t^f(d)}{p_t^A(d)}$ is ambiguous, and the change in deforestation is uncertain. Similarly, simultaneous decreases in the off-farm wage and farm-gate price lead to an uncertain change in the ratio $\frac{p_t^O(d)}{p_t^A(d)}$ and the deforestation level. If the effect of distance on the farm-gate price of agricultural goods dominates, the ratios $\frac{p_t^f(d)}{p_t^A(d)}$ and $\frac{p_t^O(d)}{p_t^A(d)}$ will increase with an increase in distance (decrease in farm-gate price), and lead to a decrease in deforestation. That is, deforestation will be negatively correlated with distance to an urban center, which is consistent with Von Thünen’s theory and previous studies. However, if the effect of distance on policy enforcement (the shadow cost of illegal deforestation) and/or on the wage for off-farm work dominates, this would result in a positive relationship between deforestation and distance.

## 3. Empirical Strategy

The objective of the empirical analysis is to estimate the marginal effect of market access – distance to urban center—on deforestation and to identify whether and how the relationship between market access and deforestation has changed over time. In the empirical model, the dependent variable is deforestation, measured by annual loss of primary forest cover (deforestation of old-growth forest). Thus, the dependent variable is non-negative, and the larger the dependent variable, the more deforestation. As postulated by the theoretical framework, deforestation is a function of labor allocated to forest clearance, which is determined by the farm-gate price of agricultural products, the shadow cost of illegal deforestation, the wage for off-farm work, land area, and characteristics of the land and household. All of the price variables are functions of distance to an urban center, which is measured as the road distance to the nearest urban center[7]. Since the extent of the road system did not change for most of our study period and study region, distance is a time-invariant variable. To incorporate the dynamic characteristics of urban centers, we include the level of urban development (as represented by the amount of nighttime light observed from outer space) and its interaction term with distance. Guided by previous studies, the characteristics of land include age of the property[8], land slope, soil quality, water access, and shape of the property. Our preliminary empirical analysis suggests that household characteristics will not affect production decision-making and could be eliminated in the deforestation model.[9] From the theoretical framework, current period deforestation depends

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[7] The urban centers are (1) six municipalities in the Ouro Preto do Oeste region: Ouro Preto do Oeste, Vale do Paraíso, Urupá, Mirante da Serra, Nova União, and Teixeirópolis; and (2) two cities immediately outside the Ouro Preto do Oeste region, Jaru and Ji-Paraná.

[8] Age of the property is years since first clearing of primary forest as observed in a library of remote sensing images starting in 1985. For properties that had forest cleared before 1985, ages are assigned based on the official settlement records from INCRA.

[9] When we include household characteristics to estimate deforestation in the same model set up using the four-waves survey data, household characteristics are insignificant in the regression results.

on the cumulative deforestation areas till the last period (Equation 10), which reflects the last period forest stock on the farm if assuming the farm lot is fully covered by forest in the initial period. We therefore control for forest stock in the last year. Considering the expected inverted-U-shape relationship between deforestation and forest cover (Busch and Engelmann 2017), we include the quadratic term of forest stock in the previous year. Furthermore, we control for temporal and spatial fixed effects. To sum up, a general form of the empirical model can be written as:

$$D_{it} = f(d_i, U_{it}, (d_i \cdot U_{it}), \overline{L}_i, Z_{it}^L, F_{i(t-1)}, {F_{i(t-1)}}^2, Y_t, S_i, \varepsilon_{it}) \tag{28}$$

where $D_{it}$ is deforested hectares for property *i* in year *t*; $d_i$ is distance to the nearest urban center for the property *i*; $U_{it}$ is the level of urban development of the nearest urban center for property *i* in year *t*; $(d_i \cdot U_{it})$ is the interaction term between distance and urban development; $\overline{L}_i$ is the lot size for property *i*; $Z_{it}^L$ includes the land characteristics mentioned above; $F_{i(t-1)}$ is primary forest cover for property *i* in year $(t-1)$; ${F_{i(t-1)}}^2$ is the quadratic term of primary forest cover for the property *i* in the year $(t-1)$; $Y_t$ represents dummy variables for calendar years; $S_i$ represents dummy variables for the agrarian settlements; and $\varepsilon_{it}$ is the error term. Based on the theoretical framework and previous studies, the expected signs of estimated coefficients are stated in Table 2.1.

The dependent variable, deforestation, is semicontinuous, with a continuous distribution except for a probability mass at zero (Olsen and Schafer 2001). The high proportion of zero values makes the normal distribution inappropriate for modelling the data (Min and Agresti 2002). Zero deforestation may occur for two reasons: (1) the farm household chooses not to expand agricultural land in the current period by clearing forest or (2) there is no forest left to clear on the property. Obviously, the second reason for zero deforestation is not driven by the covariates in equation (26) except for last year's forest stock $F_{i(t-1)}$. Therefore, we first exclude observations whose forest stock in the last year was zero[10]. Then we model the household as making decisions in two steps: First, it determines whether to deforest; second, it determines how much area to deforest. These processes can be modeled by a two-part model, such as a double hurdle model or the truncated normal hurdle model introduced by Cragg (1971). In the two-part model, the first stage is a binary model for the dichotomous event of having zero or positive deforestation values. In the second stage, Cragg suggests a truncated normal distribution to make the dependent variable positive (Wooldridge 2010). However, a simpler version for economic interpretation is: Conditional on a positive value of the dependent variable, the second stage follows a lognormal distribution (Duan et al. 1983). Beyond its simplicity, the lognormal distribution model has a well-behaved likelihood function and is typically more robust than the truncated normal model under Vuong's model selection test (Min and Agresti 2002; Hsu and Liu 2008). In contrast to the selection model, although the two-part model makes the conditional independence assumption, it also allows all covariates to appear in both parts and does not require exclusion restrictions (Olsen and Schafer 2001). This renders it appropriate for our study case, in which the decision to deforest and the extent of deforestation are driven by similar processes.

Another common approach to semicontinous data is the Tobit model. Although it censors out observations at zero and cannot interpret true zeros, it overcomes possible limitations of the two-part model. These limitations include bias in estimating small values when zeros are eliminated in the second stage and the conditional independence assumption. Hence, in addition

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[10] We drop 4896 observations, which are 2.3 percent of the sample population. We also conducted all the regressions with the original data before dropping these zero forest stock observations, and we obtained similar results.

to the two-part model, we estimate a Tobit model that combines the zero observations regime and positive observations regime into a single log-likelihood function (Engel and Moffatt 2014).

We estimate these models with panel data: 18 years of data from 8,770 farm properties. Panel data allow us to track household choices over time and control for unobserved idiosyncratic differences across households[11]. Fixed effects (FE) and random effects (RE) models are the two approaches typically used to address the panel data problem. RE supports estimation of the effects of both time-invariant and time-variant factors, and is thus preferable to FE when its key assumptions hold: the exogeneity of covariates[12] and normality of residuals. In practice, the exogeneity of covariates is often rejected in empirical analyses, which implies that the FE model is a better option. However, given that time-invariant effects are of central interest in this study (i.e., the distance to the nearest urban center), we need an alternative approach to estimate the effects of time-invariant variables and control for heterogeneity bias at the same time. One well-known approach is the adjusted RE framework model proposed by Mundlak (1978), which starts from the assumption that the heterogeneity bias of the standard RE model is the result of attempting to model "within-effects" and "between-effects" in one term. So rather than correcting heterogeneity bias, it models the bias by separating the within- and between-effects. A hybrid model (Allison 2009), or "within-between" RE formulation (Bell and Jones 2015), rearranges Mundlak's adjusted RE formulation to be more interpretable for within- and between-effects and to remove possible collinearity without the risk of heterogeneity bias.

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[11] We assume that the same household makes decisions about a given property over the entire time period. Possible justifications include that (1) legally, families that receive land in agrarian reform settlements are not allowed to sell and are expected to settle permanently, (2) in our panel data, we observe some turn-over but only on a minority of properties, and (3) we only have information on a very small fraction of the households managing the 8,770 properties in our sample,

[12] The exogeneity of covariates requires zero covariance between time-variant individual variable and the reminder residuals.

The paper adopts the within-between RE model (Bell and Jones 2015) and integrates it into a two-part model. In the first stage, a logit model is used to model the binary outcome. We define ${D_{it}}^*$ as the latent variable that satisfies the model:

$$ {D_{it}}^* = \beta_0 + \beta_1(X_{it} - \bar{X}_i) + \beta_2\bar{X}_i + \beta_3 z_i + u_i + e_{it} \tag{29} $$

And we observe $D_{it}^B$:

$$ D_{it}^B = \begin{cases} 1 & if\ {D_{it}}^* > 0 \\ 0 & if\ {D_{it}}^* = 0 \end{cases} \tag{30} $$

Given the latent variable models (29) and (30), the adjusted random effects logit model with “within-between” RE formulation can be written as:

$$ \Pr\left(D_{it}^B = 1 \middle| (X_{it} - \bar{X}_i), \bar{X}_i, z_i\right) = \Lambda(\beta_0 + \beta_1(X_{it} - \bar{X}_i) + \beta_2\bar{X}_i + \beta_3 z_i + u_i) \tag{31} $$

And the variance components model underlying the models is (Baltagi 2008):

$$ D_{it}^B = 1 \Leftrightarrow \ \beta_0 + \beta_1(X_{it} - \bar{X}_i) + \beta_2\bar{X}_i + \beta_3 z_i + \ u_i + e_{it} > 0 \tag{32} $$

where $\Lambda(\cdot)$ is the cumulative density function of the logistic distribution. $u_i$ is unobserved individual specific time invariant effect, and $e_{it}$ is the remainder disturbance. $D_{it}$ represents deforestation on farm *i* and year *t*. $X_{it}$ represents time variant individual variables for property *i* in year t. $\bar{X}_i$ represents individual $i$’s mean across all years accounting for the between effect. Thus, $(X_{it} - \bar{X}_i)$ measures variation within individuals over time accounting for the within effects. $z_i$ represents time invariant variables. $\beta_1$ represents the within effects; $\beta_2$ represents the between effects; and $\beta_3$ are coefficients of time invariant variable which accounts for between effects.

In the second stage, assuming a zero correlation between the individual-specific error terms in the two-stage models and an IHS-normal distribution[13] (Figure 2.1 in Appendix A), we conduct a conditional linear regression with the "within-between" RE model:

$$E(D_{it}|(X_{it}-\bar{X}_i),\bar{X}_i,z_i,D_{it}>0)=\beta_0+\beta_1(X_{it}-\bar{X}_i)+\beta_2\bar{X}_i+\beta_3 z_i+\ u_i+e_{it} \tag{33}$$

Besides the two-part model, we conduct an adjusted random effects Tobit model with all types of zeros. The unobserved latent variable ${D_{it}}^*$ is defined as:

$${D_{it}}^*=\beta_0+\beta_1(X_{it}-\bar{X}_i)+\beta_2\bar{X}_i+\beta_3 z_i+\ u_i+e_{it} \tag{34}$$

The observed variable $D_{it}$ is:

$$D_{it}=\begin{cases}{D_{it}}^* & if\ {D_{it}}^*>0\\ 0 & if\ {D_{it}}^*=0\end{cases} \tag{35}$$

In the regressions, the dependent variable and all explanatory variables with skewed distributions or extreme values are transformed by inverse hyperbolic sine (IHS), except for dummy variables.

The theoretical framework demonstrates that distance to urban center affects deforestation through multiple channels. As the size and relative influence of these different channels changes over time, the net effect of distance on deforestation could also change, even reversing sign. Thus, we assess whether and when the direction and size of the effect have changed, then relate that to exogenous factors associated with different channels or mechanisms. By interacting distance with year dummy variables, we start with a test of whether the effect of

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[13] The inverse hyperbolic sine (IHS) is a transformation that is defined for all values, including negative and zero (Burbidge and Magee 1988):

$$\ln\left(\theta D_{it}+(\theta^2 D_{it}^2+1)^{\frac{1}{2}}\right)/\theta=sinh^{-1}(\theta D_{it})/\theta$$

where $\theta=1$ in our transformation and the inverse sine is approximately equal to $\ln(2D_{it})$, except for small value (e.g. less than 1), so it can be interpreted in the same way as a natural logarithmic transformation (Pence 2006; Friedline et al. 2015).

distance varies by year (Figure 2.1). If test results indicate that the effect of distance does not remain constant across the study period, we then test to determine whether there are common patterns among years in order to identify possible break point(s). We use two approaches to test the observed (possible) break points. In the first approach, based on the marginal effects of distance reported in the regression, we calculate the average slope of deforestation with respect to distance in pre-break years (a linear combination of marginal effects) and the average slope in after-break years (another linear combination of marginal effects). Then we test the equality of these two multiple linear combinations at the 5% level. In the second approach, we estimate an interrupted model with potential structural break(s) that divide the effect of distance into different groups. Finally, we test the equality between sets of coefficients (both intercept and slope) in two multiple regressions (Chow 1960; Lewis-Beck 1986).

## 4. Study Area and Data Description

### 4.1 Study Area

Our study site, the Ouro Preto do Oeste region of Rondônia, is located in northwest Brazil on the western end of the "arc of deforestation" across the southern Brazilian Amazon. The climate of the region is humid tropical, with average temperatures of 24°C and annual precipitation of 2,300 mm with a distinct dry season from June to September. Native vegetation includes both dense and open tropical forests (INPE 2000; Caviglia-Harris et al. 2009).

Ouro Preto do Oeste witnessed large-scale migration and settlement beginning in the early 1970s, driven by the federal government's programs for road-building and colonization. A federal agency, the National Institute of Agrarian Colonization and Reform (INCRA), distributed land free of charge or for trivial loans at minimal or zero interest rates (Sills and Caviglia-Harris

2009). Unlike many other parts of the Amazon, land tenure is secure in the agricultural settlements in our study region (Jones et al. 1995; Sills and Caviglia-Harris 2009). Given these conditions, we model farm households as having a fixed area of land (which cannot be expanded through deforestation of additional land) with exogenous biophysical characteristics determined by INCRA's original allocation of lots.

Migration to the region continued in the 1980s, motivated by relatively fertile soils and easy access along the BR-364 interstate highway, especially after it was paved in the mid-1980s. All of the major roads in the region were paved or in the process of being paved by 2005, but side roads, and especially bridges, remain unimproved and difficult to travel on during the rainy season (Shone and Caviglia-Harris 2006). Starting from the initial four settlements created by INCRA in 1970, fourteen whole or partial settlements were created in the study region. Some latter settlements were created by INCRA and others by invasions and later regularized by INCRA. In the early 1990s, the region was subdivided into four, and later six, municipalities: Ouro Preto do Oeste, Vale do Paraíso, Urupá, Mirante da Serra, Nova União, and Teixeirópolis. The total population was over 83,000 by 2010, with 46% rural and the rest in the central city of Ouro Preto do Oeste and towns in each of the other five municipalities (IBGE 2010). In 2010, the total (urban) population of the six municipalities varied from 4,888 (1,716) to 37,928 (28,180) (IBGE 2010).

The cattle herd in Rondônia grew steadily, from minimal levels in the 1970s to the second largest among Amazonian states by 1991 (Faminow 1998). From 1997 to 2010, the growth rate of cattle herds in the Ouro Preto do Oeste region was 99%, and 173% in Rondônia; the growth rate of milk-producing cows in the Ouro Preto do Oeste region was 218%, and 215% in Rondônia (IBGE 2016). In our study region, on average, 20.1% of the land on a property was pasture in 1986, increasing to 77.6% in 2009. Creating pasture has been the immediate motivation for most deforestation in the region. Farmers in the region (especially the 83% with 100 hectares or less of land) specialize in dairy cattle. Other sources of income for farm households include annual and perennial crops, honey and fish, off-farm labor, and government payments such as pensions and school subsidies. Milk is both the largest and the most regular source of income.

### 4.2 Data Description

The data[14] consist of (1) land cover on 8,770 small farm properties (lot size less than 240 hectares[15]) in the Ouro Preto do Oeste region over 18 years (1992-2009), derived from the annual Landsat imagery archive; (2) spatial data that include the farm boundaries, road networks, market locations, and biophysical characteristics (soil, terrain, and hydrology) of the 8,770 properties, obtained from multiple Brazilian governmental agencies and supplemented with spatial data collection using GPS; (3) four waves of survey data on a stratified sample of farm households living on these properties (Caviglia-Harris, Roberts, and Sills 2014); (4) interpolated farm gate milk prices based on kriging geostatistical interpolation outcomes; and (5) the amount of nighttime light that can be observed from outer space in the 8 urban centers over the years 1992-2009[16].

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[14] The data set (1) – (3) was made available through the project "Living with Deforestation: Analyzing Transformations in Welfare and Land Use on an Old Amazonian Frontier," by Jill Caviglia Harris, Erin Sills, and Dar Roberts, NSF Project SES-0752936 (2008-2013).

[15] National policy in Brazil (11.326/2006 Política Nacional da Agricultura Familiar e Empreendimentos Familiares Rurais) defines family farmers as those owning less than 4 fiscal units of land, which is equivalent to 240 HA in Rondônia.

[16] The night-time lights are satellite-based time series data, which are available from version 4 Defense Meteorological Satellite Program – Operational Linescan System (DMSP-OLS) stable lights products. Available online: https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html

Table 2.2 provides variable definitions and descriptive statistics. Land cover is classified into seven categories: primary forest, pasture and green pasture, secondary forest, bare soil or urbanized areas, rock or savanna, water, and obscured by cloud (Roberts et al. 2002). Deforestation is defined as loss of primary forest, which in this region is mostly dense tropical forest (RADAMBRASIL 1978). Property boundaries were obtained mainly from INCRA settlement maps, which cover 9,392 properties. After excluding properties that are (1) very small (less than 1 hectare); (2) very large (larger than 240 hectares); (3) urban; (4) large forest reserves; or (5) not occupied, the sample contains 8,770 properties (Figure 2.2). The landscape covered by these 8770 farm properties contains 14 whole or partial INCRA settlements and 90% of the Ouro Preto do Oeste region's area. Distance to the nearest urban center was calculated as the minimum travel distance along the road network in the Ouro Preto do Oeste region, which was mapped using data collected during 2005 and 2009[17] with a mapping grade global positioning system (GPS) receiver and roads digitized from an INCRA settlement map (Caviglia-Harris and Harris 2008).

The household level socioeconomic data from a four-wave household survey are used in the robustness checks, section 7.1 and section 7.2. The survey data were collected in 1996, 2000, 2005 and 2009. A random sample of 196 households stratified by municipality were surveyed in 1996 and 2000. In 2005 and 2009, interviews were conducted with those same households and a supplemental sample of households in new settlements, resulting in sample sizes of 406 in 2005 and 646 in 2009.

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[17] Although road conditions may change (especially the condition of side roads in the rainy season), the road network remained almost the same during the study period (Google Earth 1984-2009). The main exceptions are the side roads around properties in settlements laid out in pie shapes (7.5% of the studied properties), which were only established in 1996.

Contemporary urban settlements and urban activities can be visually observed by the artificial illumination of buildings, transportation infrastructure, and other components of the built environment (Mellander et al. 2015). One way to measure economic activities, growth in population, and urbanization is by using the amount of nighttime light (Amaral et al. 2006; Huang et al. 2014). Using nighttime light as proxy for urban development overcomes the lack of time series socio-economic and demographic data at the subnational level (Mellander et al. 2015), and provides a reasonable way to compare urban development over regions and periods (Henderson et al. 2012). From 1992 to 2010, there were three cities in or near our study region—Jaru, Ouro Preto do Oeste, and Ji-Paraná—that had the highest light intensity and largest extent of light (Figure 2.4). Comparison of nighttime light among urban centers reflects differences in population growth, wage growth, and stages of urbanization. In the analysis, we use the sum of stable light values in all pixels in the urban center, which captures both the light intensity and the lit areas.

## 5. Results

Table 2.3 reports the estimated regression coefficients for a two-part model and a Tobit model, with both estimated using the within-between RE (WBRE) approach. For comparison purposes, results based on the standard RE and FE estimators [18] are also presented. In the WBRE approach, within and between effects are estimated separately. In contrast, a single estimated coefficient in the standard RE accounts for both within and between effects; and the coefficients in FE represent within effects only. The coefficients of within-effects in WBRE are much same as the

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[18] Fixed effects were not estimated for Tobit model, because in Tobit model (1) there does not exist a sufficient statistic allowing the fixed effects to be conditioned out of the likelihood; (2) unconditional fixed-effects estimates are biased (Greene 2004; StataCorp 2015).

corresponding coefficients in FE, as are the standard errors[19]. This indicates that WBRE performs at least as well as FE (Bell and Jones 2015). Estimations using the standard RE estimator differ more from the others, which could be due to heterogeneity bias that results from modeling time-invariant and time-variant factors in one term. In order to better interpret the interaction term as well as the estimation results in the Logit and Tobit model, we present the average marginal effects (AME) for the estimated models (Table 2.4). For the logit models in part 1, marginal effects are calculated for the probability of a positive outcome, $\Pr( {D_{it}}^* > 0)$. For the Tobit model, two types of marginal effects are presented: (a) marginal effect on the observed (censored) dependent variable, $D_{it}$ and (b) marginal effect on the latent variable, ${D_{it}}^*$.

### 5.1 Drivers of Deforestation

As reported in Table 2.3, all hypothesized drivers of deforestation are statistically significant after controlling for forest stock in the previous year, year fixed effects and settlement fixed effects. Among land characteristics, the age of the property has non-zero within-effects and between-effects. Within-effects measure variation within properties over time, and between-effects capture variation between properties. The positive signs of property age in both within-effects and between-effects in models (1) - (8) indicate that the older the property, the higher the probability of deforestation and the extent of deforestation on the property, relative to younger properties in both spatial and temporal dimensions. Other land characteristics are time-invariant regressors and demonstrate between effects. The marginal effect of average slope of the lot is significantly negative in part 2 of the two-part model, which suggests that it is costly to clear

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[19] In our analysis WBRE model does not predict exactly same within-effects as in the FE model, because we did not separate the within and between effects of the urban development (sum of night-time lights). Our robustness test shows that there is no statistically significant difference between within and between effects of the urban development.

land for agricultural use or that lower agricultural profits are expected on lots with steeper average slope. The positive sign on soil quality (percentage of the lot classified as good soil quality for agricultural production) means that deforestation is more likely to occur and that a larger deforested area is more likely on lots with a larger percentage of good soil. The indicator of easy access to surface water on the lot is positively correlated with the probability of deforestation and negatively correlated with the extent of deforestation in the two-part model, while it is less statistically significant in the model of the extent of deforestation. The Tobit model shows a positive correlation between water access and deforestation, although at a lower significance level. This positive effect of water access suggests that land is more likely to be used for agricultural production with when there is good access to water. However, the negative effect on the extent of deforestation may suggest that households retain forest along water bodies, due to law enforcement[20] and/or recognition of the value of forest watershed services. Lots laid out in a pie shape have higher probabilities of deforestation and more deforested areas, which is possibly because of different requirements for the legal reserve in pie-shape settlements. The other regressor is lot size, which has the expected positive sign.

The interaction term of distance to the nearest urban center and urban development level (sum of nighttime light) is significantly positively related to both probability of deforestation and deforestation level (Table 2.3). Holding the effect of distance to the nearest urban center and other covariates constant, the average marginal effect of urban development level is significantly negative (Table 2.4). In aggregate, the average marginal effect of distance to nearest urban center is negatively correlated to both deforestation probability and deforestation level. Specifically,

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[20] In addition to the legal reserve, the Brazilian Forest Code (law) restricts land use in Areas of Permanent Preservation (APPs), which include Riparian Preservation Areas (RPAs) that protect riverside forest buffers (Soares-Filho et al. 2014). APPs were first written in Federal Decree in 1934.

from the WBRE two-part model, a 10% increase in distance is associated with a decrease of 0.1% in probability of positive deforestation; conditional on positive deforestation, results in a 0.5% decrease in deforestation level, for about a 0.008 hectare decrease on average. This result is consistent with Von Thünen's theory and previous studies. However, it could also mask significant heterogeneity across years, which we investigate next.

### 5.2 Has the Influence of Market Access on Deforestation Changed Over Time?

By interacting the distance variable with dummies for each time period, we can investigate whether and how the effect of distance has changed across years. Holding urban development and other covariates constant, the average marginal effects of IHS-transformed distance by different years are reported in Table 2.6. The marginal effects of distance are statistically significant in most years with different signs, which suggests that the effect of distance has changed over time. The signs of the marginal effects (as with the signs of coefficients) indicate whether there would be more deforestation close to urban centers (negative sign) or far from the urban centers (positive sign). Although different models did not result in exactly the same signs and magnitudes for every year, there is clearly a common trend (Figure 2.3): Deforestation is significantly negatively related to distance in 2004 and prior years and significantly positively related to distance after 2004. The exception is 1999, when the effect of distance is significantly positive. Therefore, we propose three possible scenarios for the break point(s): (1) a single break point in 2004, (2) a single break point in 1998, and (3) two break points in 1998 and 2004. Based on the two-part model, the largest negative effect of distance on the probability of deforestation was estimated for 2003: The probability of deforestation decreases by 0.663% when distance increases by 10%. In part 2, the largest negative distance effect on deforestation level was in

1995. The largest positive distance effect on the probability of deforestation was in 2007: Deforestation probability increases by 0.462% when distance increases by 10%. The largest positive distance effect on deforestation level was in 2008.

Two approaches are employed to test the possible break point(s) of the distance effect (2004, 1998, or 1998 and 2004). In the first approach, we test the equality of these two/three linear combinations at the 5% significance level (Table 2.6). Panel A presents test results for the break year in 2004. Under the alternative hypothesis that "differences between the average effects of 2004 and pre- and post-2004 are not equal to zero," the p-value is less than 0.0001 (based on a Wald test that reports significance levels using a chi-squared distribution), so we can reject the null and conclude that the difference in means is statistically significantly different from zero. That is, the average effects of distance on deforestation are significantly different from each other in 2004 and pre- and post-2004 periods. In addition, the mean of the 2004 and pre- marginal effects of distance is significantly negative (at a 0.0001 significance level[21]), and the mean of the post-2004 marginal effects of distance is significantly positive (at a 0.0001 significance level). Panel B reports test results for 1998 as a break year. The p-value of $\chi^2$ statistic is 0.002, which suggests 1998 is a less significant break point compared with 2004. From panel C, we reject the null hypothesis of no break points in 1998 and 2004 at the same time.

In the second approach, we test the equality between sets of coefficients (both intercept and slope) in two/three regressions (Chow 1960). As reported in Table 2.7, the p-value of the $\chi^2$ statistic (based on a Wald test) is less than 0.001 for all three scenarios for structural break(s), which suggests that we reject the null hypothesis of no structural break(s). However, compared

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[21] The exception is part 2 in the Two-part model, where the mean of marginal effects is negative at a lower significance level.

with the average marginal effect of the 2004 and pre- and post-2004(at 0.0001 significance level), the average marginal effect of distance in the years after 1998 is insignificant (at a 0.44 significance level in model (1)); the average marginal effect of distance in years between 1998 and 2004 is also insignificant (at a 0.493 level in model (1) and at a 0.028 level in model (7) and (8)). Overall, the break point of 2004 is relatively more statistically significant.

## 6. Discussion

Analysis results reveal that the effect of distance to the nearest urban center on deforestation changed over the study period, from significantly negative to significantly positive, starting in 2005. According to the theoretical framework, if the effect of distance on farm-gate price of agricultural goods dominates, the relationship between deforestation and distance is expected to be negative. This appears to apply to 2004 and pre-years. In more recent years, the effects of distance on policy enforcement, on the wage for off-farm work, and/or on factors that influence household utility through distance (e.g. getting health care and education for children) may dominate, which explains why the relationship between deforestation and distance becomes positive. Thus, we investigate (1) the development of milk markets (the dominant agricultural product) and transportation cost, (2) environmental legislation and protection policies over the study period, and (3) the development of urban centers which may indicate changes in off-farm wages, availability of labor to hire onto farm, and other factors that influence household utility through distance.

### 6.1 Milk Markets

In the early 1980s, no milk-processing facilities were observed and milk production was mainly for self-consumption in the region (Leite and Furley 1985). However, by 1991, 70% of farmers produced milk and 80% of the milk was sold to milk plants in Ji- Paraná and Ouro Preto do Oeste (Pedlowski and Dale 1992). According to a household survey conducted in 1991 (Pedlowski and Dale 1992), in the Ouro Preto do Oeste region, milk plants sent collection trucks to collect milk at each farm's "gate" daily, and farmers had to pay a premium for transporting their milk to the plants. The transportation cost paid by farmers amounted to 22% of the value of milk production. In a 2005 household survey (Caviglia-Harris, Roberts, and Sills 2014), no farmers reported being directly charged for transportation of their milk. The number of milk processing plants had increased from 11 in pre-1996 years to 19 in 2005, increasing competition among the plants, possibly leading them to waive the transportation fee to motivate farmers to become their suppliers (Saha 2008). Since 15 out 19 dairies in the region in the study periods were located in or next to urban centers (Saha 2008), distance to urban centers could be a reasonable proxy for distance to milk markets. This fading role of transportation cost could be partly responsible for the observed change in the effect of distance to urban center.

### 6.2 Policy Enforcement

The requirement to maintain a legal reserve of forest on each property in the Brazilian Forest Code is the most significant regulatory constraint for land use decision making in the study region. Initiated in 1934 (Federal Decree No. 23793) and redefined in 1965 (Federal Decree No.7731), the Forest Code has required that landowners maintain 20% to 80% of their rural properties under native vegetation in different time periods and different regions, depending on the property’s vegetation type, location, and size (Soares-Filho et al. 2014; Brancalion et al. 2016). Beginning in 1989, environmental laws became more encompassing and scientific; however, these requirements were challenging to enforce and compliance was difficult to monitor (Drummond and Barros-Platiau 2006; Soares-Filho et al. 2014). Deforestation rates in Rondônia as well as in the Brazilian Legal Amazon, rose rapidly from 1990 to 2004 (Figure 2.4), and Brazil had the world’s highest rate of deforestation. In 2004, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) was launched, which is a well-established policy turning point (Assunção et al. 2012; Dalla-Nora et al. 2014). After peaking at 27,423 square kilometers per year in 2004, deforestation in the Legal Amazon and Rondônia had dropped by 73% by 2009.

The PPCDAm was the first time that multiple government institutions in the Brazilian federal government were directed to cooperate and take action to combat deforestation. The plan included the National Institute for Space Research (INPE), the Federal Police, the Federal Highway Police, and the Brazilian Army (IPAM, 2009). One significant change under the PPCDAm framework was the stronger monitoring power for deforestation. The Real-Time System for Detection of Deforestation (DETER) was introduced, which improved remote sensing-based Amazon monitoring capacity. DETER was able to detect deforested areas larger than 25 hectares in 15-day intervals and issue an alert that an area is endangered (Assunção et al. 2014). This enables environmental police and enforcement personnel to go to the endangered area and potentially both prevent further deforestation and apprehend those responsible (Faleiros 2011; Popkin, 2016).

Under this system of monitoring and controlling deforestation, the closer to an urban center, the higher the law enforcement power. Although remote sensing monitors the entire landscape, reaction time between the monitoring alert and law enforcement action varies with distance from the nearest law enforcement office. Because offices are located in cities and personnel face significant transportation constraints, landowners face a higher risk of being caught for illegal clearing or burning of land located closer to the urban center. Thus, the positive relationship between deforestation and distance to urban center in post-2004 years may be partly due to increased influence of law enforcement.

### 6.3 Urban Development

Another possible explanation for the positive relationship between distance and deforestation is that the effect of off-farm wage dominates. The closer to an urban center， the lower the transportation cost of off-farm employment, which may lead the household to allocate family labor to off-farm employment rather than clearing forest. The distinction between wages from urban employment and income in rural sectors affects the evolution of deforestation on the frontier. According to standard urban economic theory, wages are higher in urban centers due to greater demand and cheaper inputs (Fujita 1989). Also, a large body of evidence suggests a positive relationship between urban size and wages (Glaeser and Mare 2001; Partridge et al. 2009). Thus, growth of urban economies is likely to correlate with growth in wages over time. On the other hand, growth of urban economics is also likely to correlate with growth of the urban population, which is believed to be positively correlated with deforestation (Angelsen 1999; DeFries et al.  2010). Yet a third perspective from classic models of urbanization is that as the deforestation frontier closes, the redistribution of population from rural areas to cities intensifies, alleviating the pressure for agricultural land (Walker 1993; Simmons et al. 2002). Thus, the relationship between urban development, or the growth of the urban economy, and the spatial pattern of deforestation is an empirical issue.

In the previous regression analysis, we used the sum of nighttime light as a proxy for urban development and included the sum of lights in the nearest urban center and its interaction term with distance to the nearest urban center. To facilitate interpretation, in this section, we use nighttime light to categorize urban centers into two groups, small and large urban, and then analyze how those categories moderate the effect of distance on deforestation. The cutoff point between small and large urban is the lowest tertile of the sum of lights. Figure 2.5 reports average marginal effects of IHS-transformed distance by year and two categories of urban centers. Again, the effect of distance on deforestation clearly changes over time. In 2004 and prior years, deforestation is negatively related to distance to the nearest urban center, regardless of urban size; however, the magnitude of the effect of distance to small urban is greater in most cases. After 2004, deforestation becomes positively related to distance to the nearest urban center on properties closest to a large urban center.

Based on the results reported in Figure 2.5, Figure 2.6 graphs the relationship between distance and deforestation, conditional on urban size, before and after the 2004 break point. In 2004 and prior years, the negative distance effect may be due to the dominant effect of agricultural transportation cost, and the smaller effect associated with large urban centers may due to better road networks in those areas. After 2004, higher wages in large urban centers may have increased the opportunity cost of labor invested in deforestation and agriculture. That is, the positive effect of distance post-2004 may be triggered by the dominant effect of urban wages.

## 7. Robustness Checks

### 7.1 Testing the Effects of Forest Stock

While the positive effect of distance on deforestation could be due to the increasing scarcity of forest as the frontier evolves, the relationship holds true after controlling for forest stock. In order to further test for robustness, we (1) regress deforestation percentage (annual loss of forest cover relative to forest cover in the previous year), and (2) test whether the effects of distance hold after controlling for forest stock in the neighborhood around each lot (1 km buffer around the property centroid). Table 2.8 reports average marginal effects of IHS-transformed distance from the above two models. Distance effects still exhibit clear change patterns: They are significantly negatively related to deforestation in 2004 and pre-, and positively related to deforestation post-2004.

### 7.2 Kriging Analysis on Farm Gate Prices

The above analysis demonstrates multiple dimensions of market distance effect on deforestation. One mechanism by which distance affects deforestation is through the farm gate prices of agricultural output. The objective of this section is to examine whether distance to market is a good proxy for farm gate price. The four-wave household survey in the study region recorded farm gate prices in both dry and wet seasons of the survey years (1996[22], 2000, 2005, and 2009). Based on farm gate price “points” from the survey, the study employs the kriging geostatistical interpolation method to generate farm gate price surfaces, which indicate spatial variations in farm gate prices that correspond to the location of urban centers.

The kriging geostatistical interpolation method was used to generate the unknown farm gate price surface based on known price points from the household survey. Kriging assumes that

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[22] For 1996, farm gate milk prices were the average of wet and dry seasons.

the distance[23] between sample points reflects a spatial correlation that can be used to explain variation in the surface (Oliver and Webster 1990). According to von Thünen theory, there exist spatial differentials in farm gate prices relating to differences in transport costs to major urban centers, which are determined by the distance to major urban centers. That is, the spatial correlation among prices on survey lots can be used to interpolate a price surface. I assume that farm gate price data points and the associated surface at nearby locations are more similar to each other than price points at locations distant from each other.

Considering the dominance of milk production in the study region, the analysis treats milk as the only agricultural product and assumes that pasture land is solely for raising dairy cattle. Farm gate milk price points were from farm-producer-reported price in the four-wave household survey adjusted for inflation. The study uses the ordinary kriging method,[24] which assumes that the constant mean is unknown. The first step in predicting the unknown surface is to estimate spatial autocorrelation values using either semivariogram or covariance functions. After comparing the fitness of different models, a Gaussian semivariance model was used in the analysis. Eight farm gate milk price surfaces were generated: surfaces for dry and wet seasons in four years (Figure 2.7-2.8).

In Figure 2.7-2.8, areas with higher farm gate milk prices are redder (darker); red points represent urban centers, and blue triangles are active dairy plants. For the years 1996 and 2000, clear cluster patterns for milk prices are evident: The highest prices were concentrated in the southwest, especially around Mirante da Serra and Nova União; middle prices were in the middle area around the central city, Ouro Preto do Oeste; lower prices were in the southeast and northeast; and the lowest prices were clustered in the northeastern part of the region. In 2005, the

---

[23] Distance in the kriging analysis refers to Euclidean distance.
[24] For more detailed discussion of geostatistical modeling, see, for example, Cressie (1988), Zimmerman et al. (1999), and Schabenberger and Gotway (2017).

highest farm gate milk prices were spread over the southwest, south, middle, and north, but cluster patterns were still present. It is also generally true that the closer to an urban center, the higher the farm gate price. In 2009, even after adjusting for inflation, farm gate milk prices were increasing greatly across the region, especially in the dry season. The cluster pattern becomes less clear in the dry season and clearer in the wet season, by which prices are higher near urban centers.

We cannot reject the hypothesis that there is a negative relationship between farm gate price and distance to urban center. We observe, however, that this relationship has changed over time and over space.

### 7.3 Other Specifications on Market Access

In the analysis above, market access is represented by distance to the nearest urban center (three major cities and five municipalities). Since the offices of policy enforcement authorities (IBAMA and SEDAM) are located in one of the major cities, Ji-Paraná, we test the effect of distance to Ji- Paraná. As reported in Table 2.9, the general average marginal effects of distance to Ji-Paraná on deforestation were significantly positive (The exceptions are 1999 and post-2007). This suggests that policy enforcement would be a key mechanism for the effect of distance to urban center.

## 8. Conclusion

Market access, represented by distance to urban center, has multiple dimensions with different effects on deforestation. The mechanisms by which distance could affect deforestation include the farm-gate price of agricultural output, wage for off-farm labor, and shadow cost of illegal deforestation (policy enforcement). The relationship between distance to urban center and deforestation does not remain constant, and is determined by the dominant mechanisms in particular periods and regions. With a 18-year panel on 8770 farm properties in the Ouro Preto do Oeste region of Rondônia, our empirical results show that after controlling for forest stock, urban development level and other drivers of deforestation, the effect of distance to the nearest urban center on both deforestation probability and deforestation level has changed over time. Specifically, the average effect of distance to the nearest urban center was significantly negatively correlated with deforestation in 2004 and pre-2004, but positively correlated with deforestation in post-2004. Supported by structural break tests, 2004 is the most significant break point.

This structural break suggests that the increased monitoring and control of deforestation after 2004 affected the spatial pattern of deforestation, encouraging more deforestation further from urban centers. We identify two other potential factors that could have led to the change in the effect of distance on deforestation. The first is the diminishing role of transportation costs as milk markets developed and greater competition among dairies reduce the effect of distance to the nearest urban center on the farm-gate price of milk. The second is the increasing role of access to urban labor markets, meaning a stronger negative correlation between distance to market and the opportunity cost of household labor in deforestation and agriculture. However, neither the changing role of transportation in farm gate prices nor the development of urban economies (and with them, urban labor markets) underwent any distinct changes in 2004, suggesting that although they are factors in the changing role of distance, the new policy regime introduce in 2004 likely played an important role.

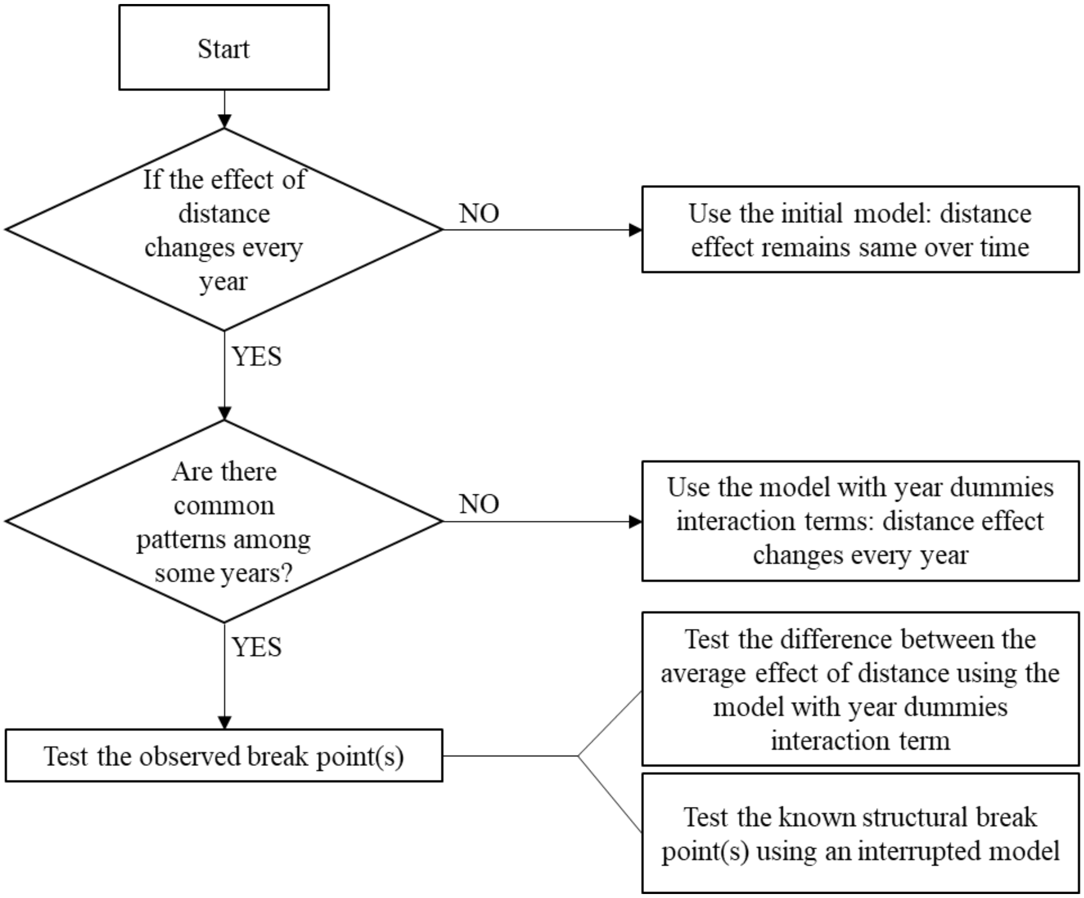

Figure 2.1. Steps of analyzing if and how the effect of distance changes over time

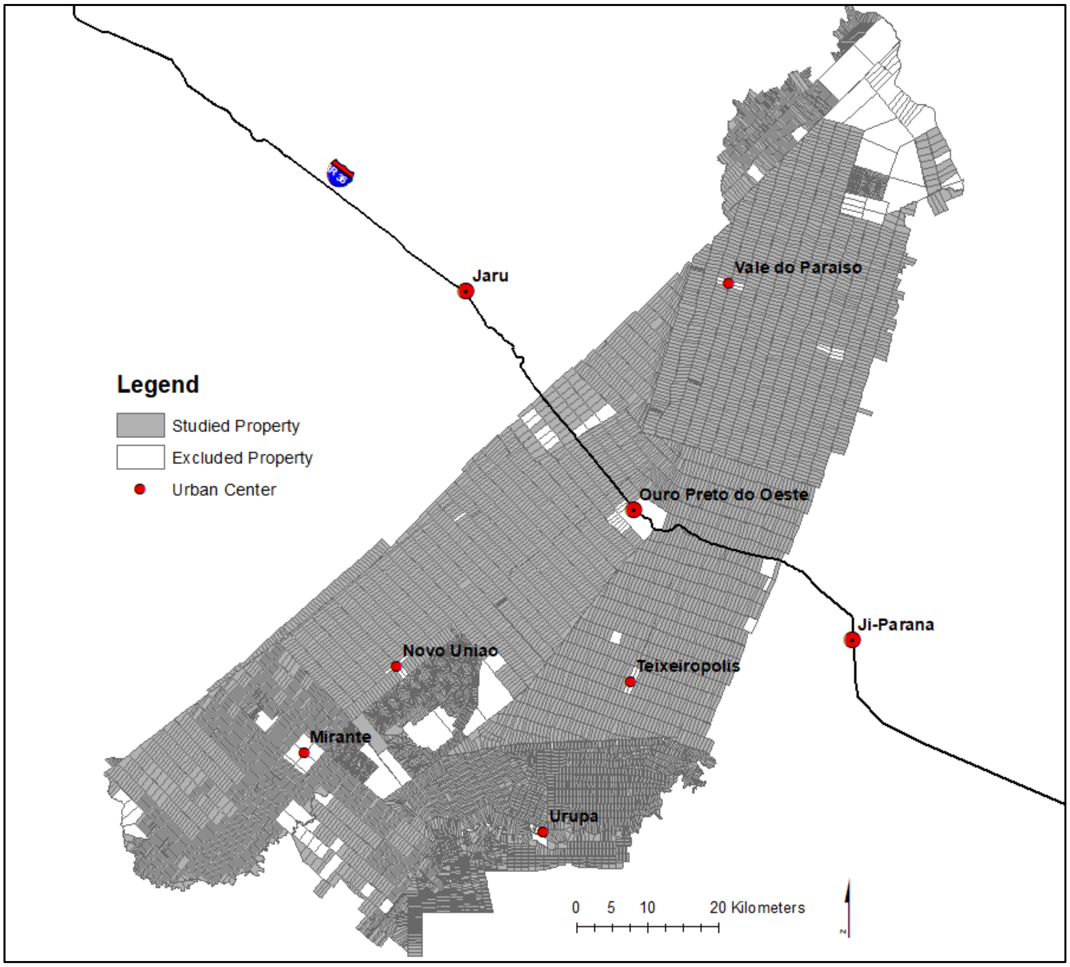

Figure 2.2. Studied Properties (n=8770) in the Ouro Preto do Oeste Region

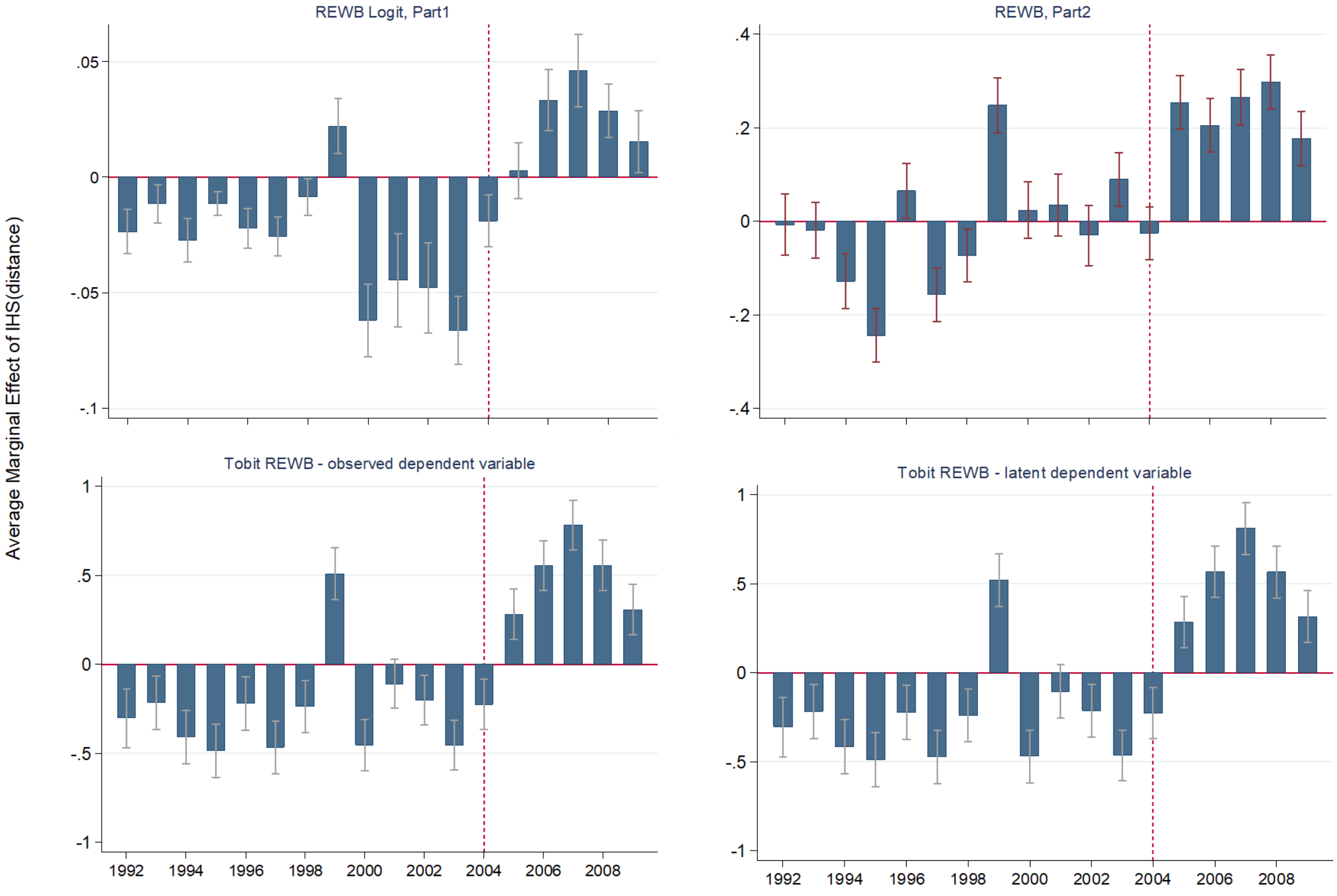

Figure 2.3. Average Marginal Effect of IHS(distance) by different years

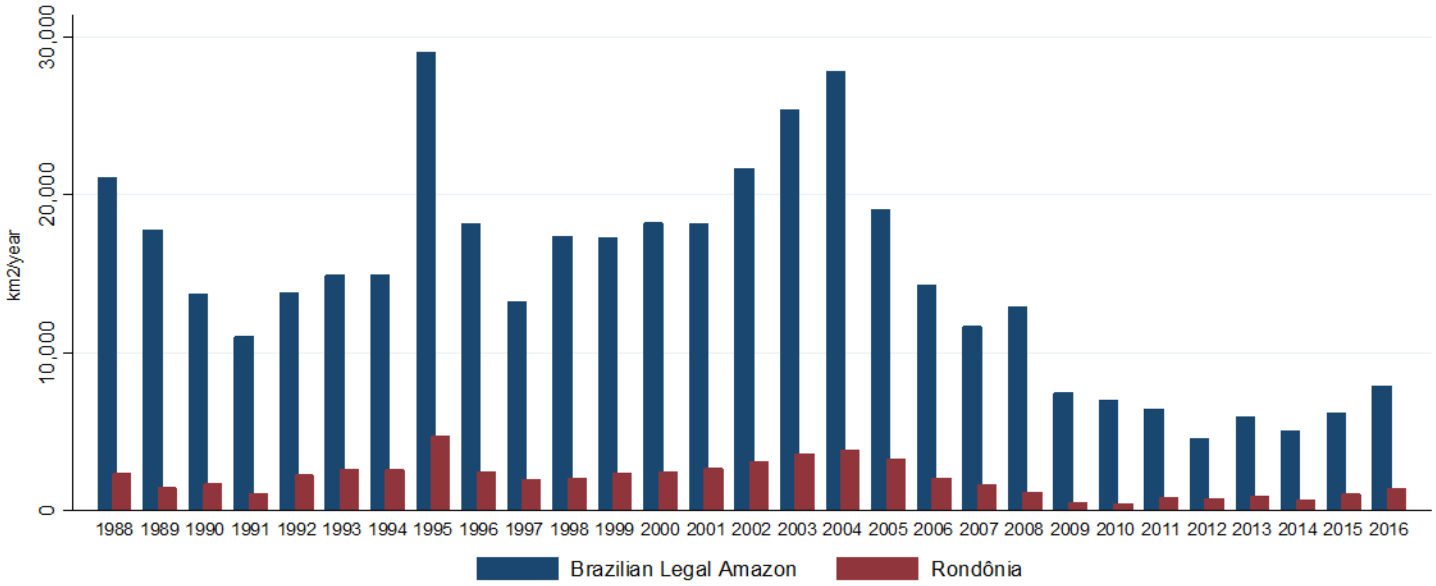

Figure 2.4. Annual Rate of Deforestation in Rondônia and Brazilian Legal Amazon

*Source*: INPE (2017)

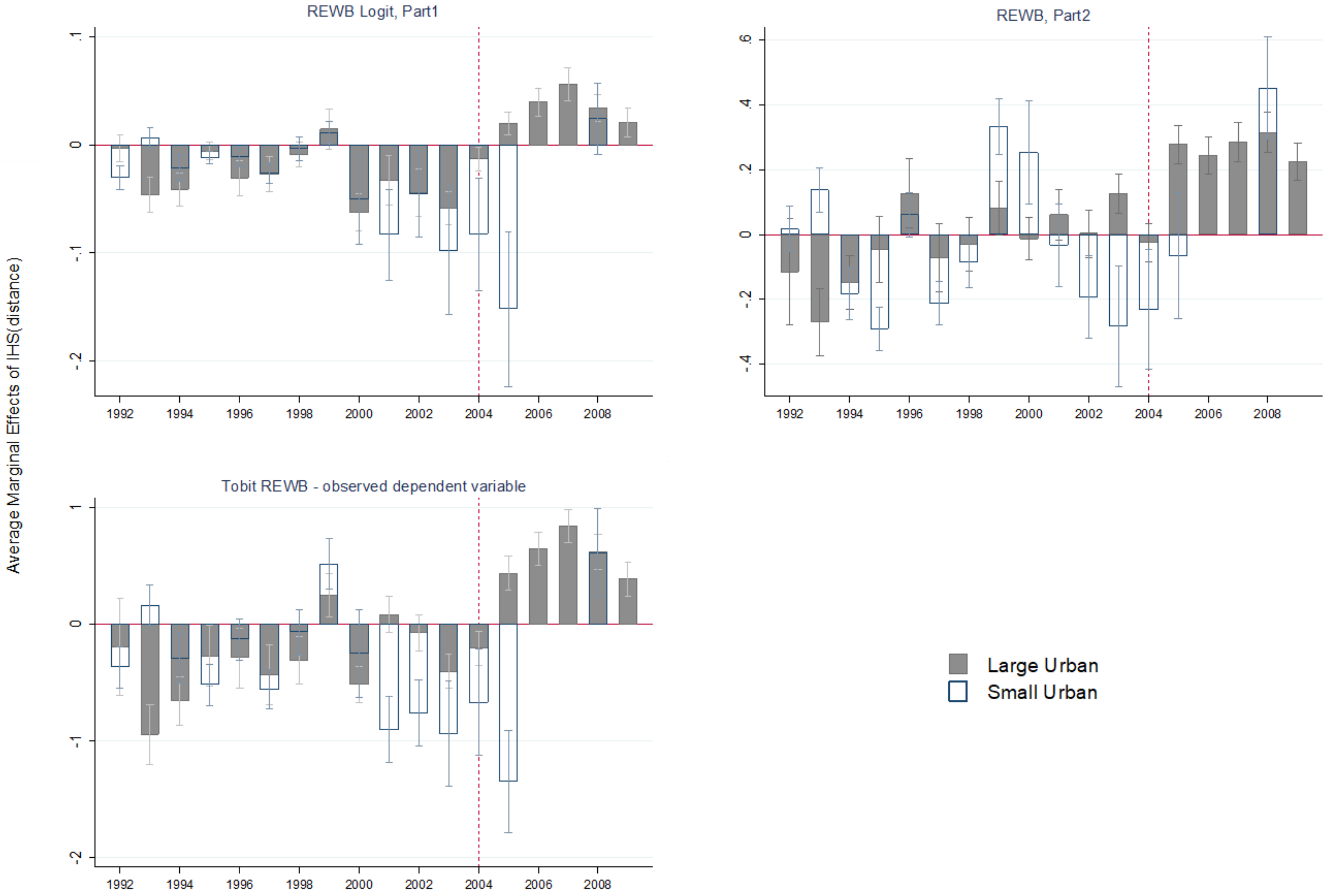

Figure 2.5. Average Marginal Effects of IHS(distance) by Year and Urban Size

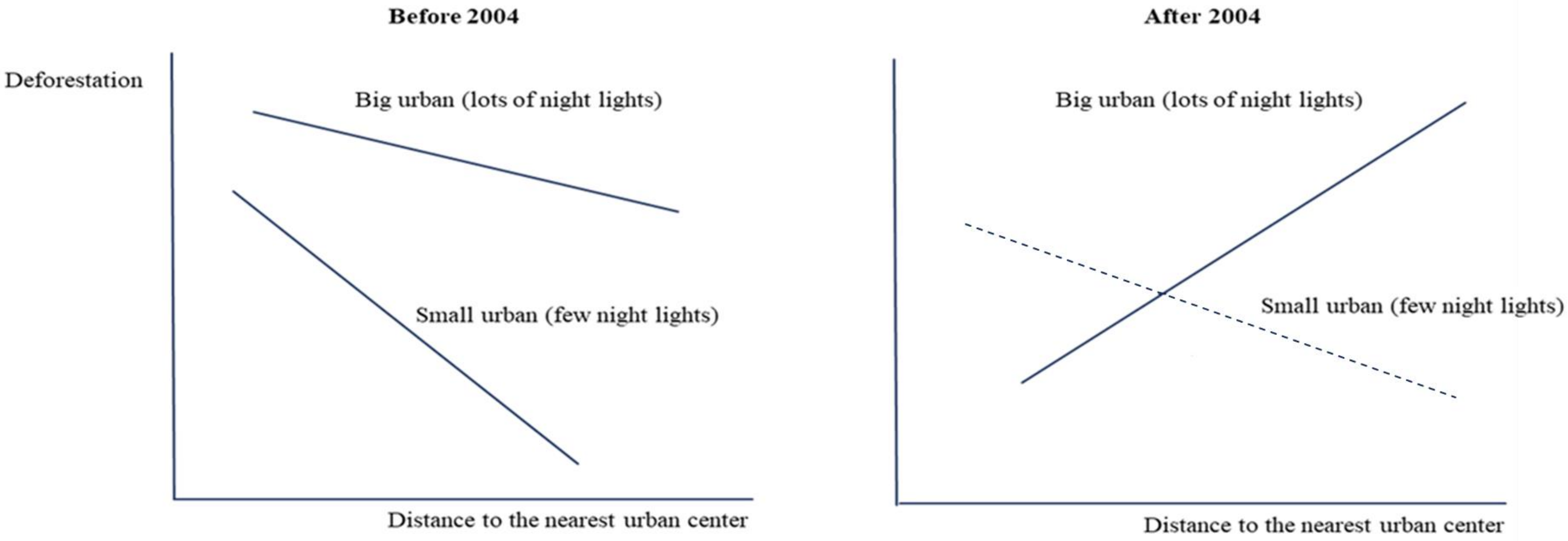

Figure 2.6. The Relationship Between Urban Size and Distance Effect on Deforestation

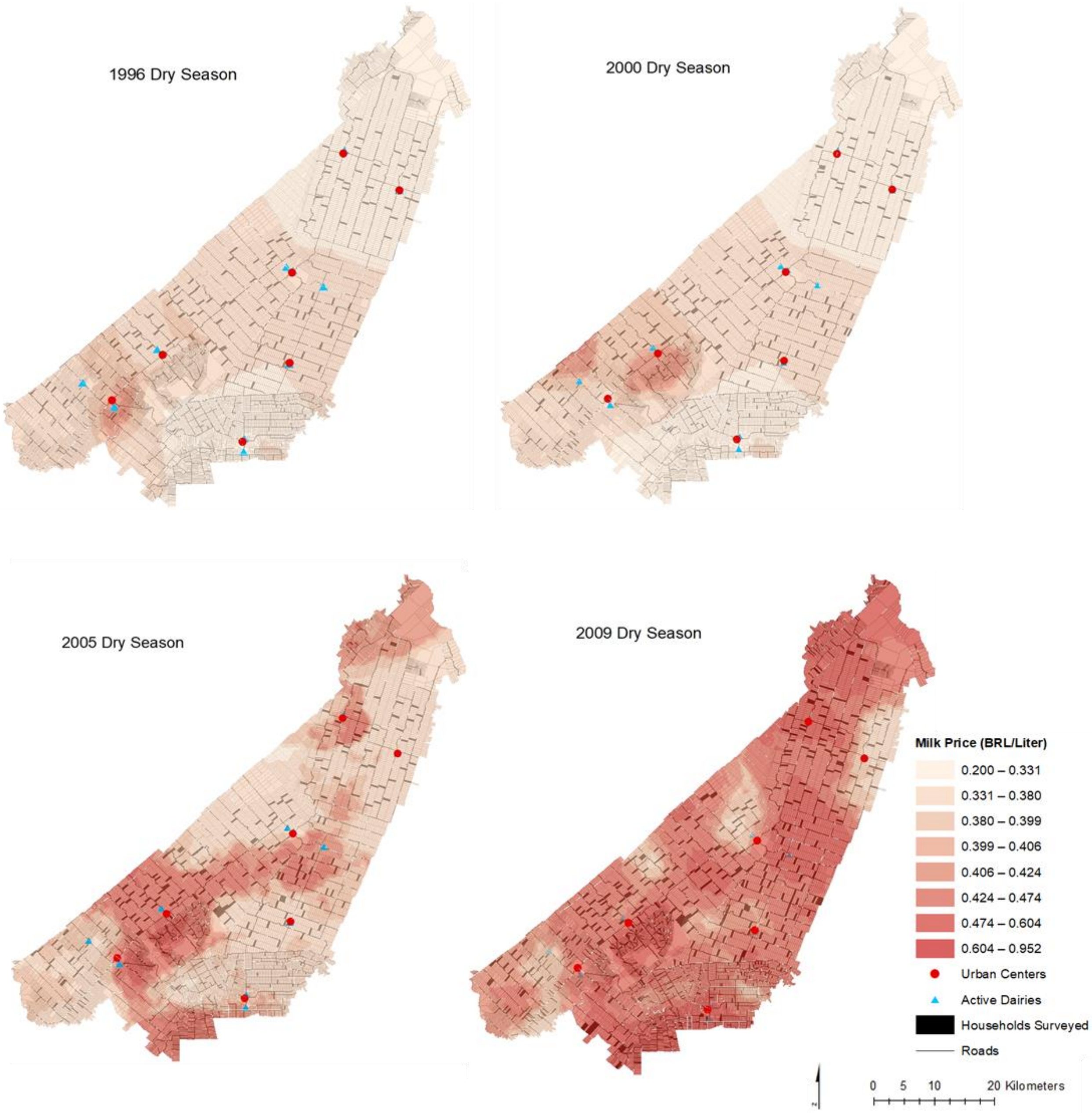

Figure 2.7. Kriging Milk Price Surfaces in Dry Seasons

Figure 2.8. Kriging Milk Price Surfaces in Wet Seasons

Table 2.1. Expected Signs of the Estimated Coefficients

| | **Variables** | **Expected Signs of the Coefficients** |
|---|---|---|
| $d_i$ | distance | -/+ |
| $U_{it}$ | urban development level (nighttime light value) | -/+ |
| $(d_i \cdot U_{it})$ | interaction term between distance and urban development | -/+ |
| $\overline{L}_i$ | lot size for property | + |
| | age of the property | + |
| | land slope | - |
| $Z_{it}^{L}$ | soil quality | + |
| | water access | -/+ |
| | shape of the property | + |
| $F_{i(t-1)}$ | forest stock in last year | + |
| ${F_{i(t-1)}}^2$ | quadratic term of forest stock in last year | - |

Table 2.2. Variable Definitions and Descriptive Statistics

| Variable | Definition | Mean | Std. Dev. | Min | Max | Observations |
|---|---|---|---|---|---|---|
| ***Dependent variable*** | | | | | | |
| deforestation | Deforestation areas: annual loss of primary forest cover on the lot, in hectares. | 1.646 | 3.396 | 0 | 153.403 | 153315 |
| ***Market access*** | | | | | | |
| distance | Road distance to the nearest urban center ( Jaru, Ji-Paraná, Mirante da Serra, Nova União,Ouro Preto do Oeste, Teixeirópolis, Urupá, Vale do Paraíso), in meters. | 17.963 | 8.853 | 0.845 | 54.527 | 153315 |
| lights | Sum of stable lights values in all pixels in the urban center | 384.132 | 568.616 | 0.000 | 7012.000 | 153315 |
| ***Characteristics of Land*** | | | | | | |
| property age | Age of the property are years since first primary forest cleared. When the properties have forest cleared before 1985 (the first year of the study period), the ages were based on the official settlement records from INCRA. | 19.513 | 11.418 | 0 | 39 | 153315 |
| slope | Weighted average of lot slope, calculated using the percentage of the lot in each 5% inclination class, from 0% to 50%. | 4.109 | 2.065 | 2.500 | 22.284 | 153315 |
| soil quality | Percentage of the lot's area classified as good for agriculture. | 0.013 | 0.105 | 0 | 1 | 153315 |
| water access | Dummy variable, whether the lot has relatively easy access to water sources (main rivers and/or bodies of water). | 0.358 | 0.479 | 0 | 1 | 153315 |
| pie shape | Dummy variable, whether the lot has a pie shape. | 0.074 | 0.261 | 0 | 1 | 153315 |
| ***Other control variables*** | | | | | | |
| forest cover $_{(t-1)}$ | Primary forest cover (hectares) in the last year on the lot. | 22.597 | 22.640 | 0.100 | 239.355 | 153315 |
| lot size | Size of the property measured in hectares. | 62.874 | 37.689 | 1.288 | 239.993 | 153315 |

Table 2.3. Drivers of Deforestation (Estimated Regression Coefficients)

| | Two-part Model | | | | | | Tobit Model |
|---|---|---|---|---|---|---|---|
| | Part 1 | | | Part 2 | | | |
| Variable | (1) Logit WBRE | (2) Logit RE | (3) Logit FE | (4) WBRE | (5) RE | (6) FE | (7) Tobit WBRE |
| ***Within-effects*** | | | | | | | |
| (forest cover $_{(t-1)}$) within-effect | 0.094*** | 0.079*** | 0.154*** | 0.083*** | 0.052*** | 0.086*** | 0.131*** |
| | (0.003) | (0.002) | (0.004) | (0.001) | (0.001) | (0.001) | (0.002) |
| (forest cover $_{(t-1)}$)$^2$ within-effect | -0.001*** | -0.001*** | -0.002*** | -0.001*** | -0.0004*** | -0.001*** | -0.001*** |
| | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| ihs (property age) within-effect | 0.754*** | 0.554*** | 0.761*** | 0.191*** | 0.122*** | 0.153*** | 0.728*** |
| | (0.038) | (0.032) | (0.041) | (0.016) | (0.013) | (0.016) | (0.037) |
| ***Between-effects*** | | | | | | | |
| (forest cover $_{(t-1)}$) between-effect | 0.069*** | | | 0.028*** | | | 0.097*** |
| | (0.002) | | | (0.001) | | | (0.003) |
| (forest cover $_{(t-1)}$)$^2$ between-effect | -0.0004*** | | | -0.0002*** | | | -0.001*** |
| | (0.000) | | | (0.000) | | | (0.000) |
| ihs (property age) between-effect | 0.307*** | | | 0.008 | | | 0.274*** |
| | (0.043) | | | (0.017) | | | (0.048) |
| ihs (distance) | -1.262*** | -1.347*** | | -0.152*** | -0.228*** | | -0.496*** |
| | (0.098) | (0.098) | | (0.023) | (0.023) | | (0.063) |
| ihs (lights) | -2.077*** | -2.230*** | -2.427*** | -0.439*** | -0.504*** | -0.438*** | -0.935*** |
| | (0.156) | (0.156) | (0.177) | (0.038) | (0.038) | (0.042) | (0.097) |
| ihs (distance) * ihs (lights) | 0.187*** | 0.201*** | 0.215*** | 0.037*** | 0.043*** | 0.036*** | 0.082*** |
| | (0.015) | (0.015) | (0.017) | (0.004) | (0.004) | (0.004) | (0.009) |
| ihs (slope) | 0.015 | 0.012 | | -0.070*** | -0.152*** | | -0.076 |
| | (0.050) | (0.050) | | (0.018) | (0.018) | | (0.055) |
| ihs (lot size) | 0.672*** | 0.596*** | | 0.555*** | 0.301*** | | 1.007*** |
| | (0.055) | (0.050) | | (0.021) | (0.020) | | (0.062) |

Table 2.3. (continued)

| | Two-part Model | | | | | | Tobit Model |
|---|---|---|---|---|---|---|---|
| | Part 1 | | | Part 2 | | | |
| Variable | (1) Logit WBRE | (2) Logit RE | (3) Logit FE | (4) WBRE | (5) RE | (6) FE | (7) Tobit WBRE |
| soil quality | 0.465*** | 0.469*** | | 0.206*** | 0.247*** | | 0.527*** |
| | (0.179) | (0.178) | | (0.058) | (0.059) | | (0.179) |
| water access (dummy) | 0.096*** | 0.089*** | | -0.013 | -0.029** | | 0.071* |
| | (0.035) | (0.034) | | (0.013) | (0.013) | | (0.038) |
| pie shape (dummy) | 0.856*** | 0.775*** | | 0.217*** | 0.145*** | | 1.350*** |
| | (0.128) | (0.127) | | (0.051) | (0.052) | | (0.147) |
| constant | 6.541*** | 8.061*** | | 3.681*** | 7.915*** | 7.709*** | -0.539 |
| | (1.330) | (1.298) | | (0.391) | (0.373) | (0.063) | (1.118) |
| $\sigma_u$ | 1.080 | 1.074 | | 0.397 | 0.403 | 0.811 | 1.383 |
| $\sigma_e$ | | | | 1.319 | 1.319 | 1.319 | 3.368 |
| $\rho$ | 0.262 | 0.260 | | 0.083 | 0.085 | 0.274 | 0.144 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Settlement fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Number of observations | 136,204 | 136,204 | 94,626 | 117,881 | 117,881 | 117,881 | 136,204 |
| Number of groups (properties) | 8,714 | 8,714 | 5,780 | 8,704 | 8,704 | 8,704 | 8,714 |

*Note*: The dependent variable in models of part 1 is 1, if the (IHS transformed) annual deforested areas larger than zero; The dependent variable in models of part 2 is IHS transformed annual deforested areas; The dependent variable in the tobit models is IHS transformed annual deforested areas, if the (IHS transformed) annual deforested areas larger than zero, and is zero if otherwise.

Standard errors in parenthesis; "***", "**", "*", indicate significance at the 1%, 5%, and 10% levels. $\sigma_u$ and $\sigma_e$ denote the standard deviation of $u_i$ and $e_{it}$; $\rho$ is the proportion of the total variance contributed by the individual specific effect.

Table 2.4. Average Marginal Effects (AME) for the Estimated Models

| | Two-part Model | | | | | | Tobit Model | |
|---|---|---|---|---|---|---|---|---|
| | Part 1 | | | Part 2 | | | | |
| | (1) Logit WBRE | (2) Logit RE | (3) Logit FE | (4) WBRE | (5) RE | (6) FE | (7) Tobit WBRE-observed dependent variable | (8) Tobit WBRE-latent dependent variable |
| ***Within-effects*** | | | | | | | | |
| (forest cover $_{(t-1)}$) within-effect | 0.008*** | 0.007*** | 0.011*** | 0.083*** | 0.052*** | 0.086*** | 0.127*** | 0.131*** |
| | (0.000) | (0.000) | (0.001) | (0.001) | (0.001) | (0.001) | (0.002) | (0.002) |
| (forest cover $_{(t-1)}$)$^2$ within-effect | -0.00007*** | -0.00005*** | -0.0001*** | -0.0006*** | -0.0003*** | -0.0006*** | -0.001*** | -0.001*** |
| | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| ihs (property age) within-effect | 0.063*** | 0.046*** | 0.056*** | 0.191*** | 0.122*** | 0.153*** | 0.711*** | 0.728*** |
| | (0.003) | (0.003) | (0.003) | (0.016) | (0.013) | (0.016) | (0.036) | (0.037) |
| ***Between-effects*** | | | | | | | | |
| (forest cover $_{(t-1)}$) between-effect | 0.006*** | | | 0.028*** | | | 0.095*** | 0.097*** |
| | (0.000) | | | (0.001) | | | (0.002) | (0.003) |
| (forest cover $_{(t-1)}$)$^2$ between-effect | -0.00004*** | | | -0.0002*** | | | -0.0007*** | -0.0007*** |
| | (0.000) | | | (0.000) | | | (0.000) | (0.000) |
| ihs (property age) between-effect | 0.026*** | | | 0.008 | | | 0.267*** | 0.274*** |
| | (0.004) | | | (0.017) | | | (0.047) | (0.048) |
| ihs (distance) | -0.011*** | -0.011*** | 0.097*** | 0.050*** | 0.004 | 0.196*** | -0.048 | -0.048 |
| | (0.003) | (0.003) | (0.012) | (0.012) | (0.012) | (0.022) | (0.036) | (0.037) |
| ihs (lights) | -0.013*** | -0.013*** | -0.019*** | -0.053*** | -0.060*** | -0.063*** | -0.088*** | -0.090*** |
| | (0.001) | (0.001) | (0.002) | (0.003) | (0.003) | (0.004) | (0.008) | (0.008) |
| ihs (slope) | 0.001 | 0.001 | | -0.070*** | -0.152*** | | -0.075 | -0.076 |
| | (0.004) | (0.004) | | (0.018) | (0.018) | | (0.054) | (0.055) |

Table 2.4. (continued)

| | Two-part Model | | | | | | Tobit Model | |
|---|---|---|---|---|---|---|---|---|
| | Part 1 | | | Part 2 | | | | |
| | (1) Logit WBRE | (2) Logit RE | (3) Logit FE | (4) WBRE | (5) RE | (6) FE | (7) Tobit WBRE-observed dependent variable | (8) Tobit WBRE-latent dependent variable |
| ihs (lot size) | 0.056*** | 0.050*** | | 0.555*** | 0.301*** | | 0.983*** | 1.007*** |
| | (0.005) | (0.004) | | (0.021) | (0.020) | | (0.060) | (0.062) |
| soil quality | 0.039*** | 0.039*** | | 0.206*** | 0.247*** | | 0.515*** | 0.527*** |
| | (0.015) | (0.015) | | (0.058) | (0.059) | | (0.175) | (0.179) |
| water access (dummy) | 0.008*** | 0.007** | | -0.013 | -0.029** | | 0.069* | 0.071* |
| | (0.003) | (0.003) | | (0.013) | (0.013) | | (0.038) | (0.038) |
| pie shape (dummy) | 0.070*** | 0.064*** | | 0.217*** | 0.145*** | | 1.319*** | 1.350*** |
| | (0.011) | (0.011) | | (0.051) | (0.052) | | (0.144) | (0.147) |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Settlement fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Number of observations | 136,204 | 136,204 | 94,626 | 117,881 | 117,881 | 117,881 | 136,204 | 136,204 |
| Number of groups (properties) | 8,714 | 8,714 | 5,780 | 8,704 | 8,704 | 8,704 | 8,714 | 8,714 |

*Note*: These are average marginal effects (the average of the individual marginal effects) from the estimated models. For WBRE adjusted Tobit model, there are two types of marginal effects of interest in the paper: a) marginal effect on the observed (censored) dependent variable, $D_{it}$; b) marginal effect on the latent variable, $D_{it}{}^{*}$.

Standard errors in parenthesis; “***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

Table 2.5. Average Marginal Effect of IHS(distance) by Different Years

| | Two-part Model | | Tobit model | | | |
|---|---|---|---|---|---|---|
| | Part 1 | Part 2 | | | | |
| | (1) Logit WBRE | (4) WBRE | (7) Tobit WBRE- observed dependent variable | (8) Tobit WBRE- latent dependent variable | p($F01_{t-1} > 0$) | p(DF > 0) |
| 1992 | -0.0235*** | -0.00691 | -0.304*** | -0.306*** | 99.81% | 82.77% |
| 1993 | -0.0115*** | -0.0189 | -0.215*** | -0.218*** | 99.81% | 84.19% |
| 1994 | -0.0272*** | -0.128*** | -0.410*** | -0.415*** | 99.77% | 85.45% |
| 1995 | -0.0115*** | -0.243*** | -0.486*** | -0.489*** | 99.64% | 93.51% |
| 1996 | -0.0221*** | 0.0651** | -0.219*** | -0.222*** | 99.44% | 89.48% |
| 1997 | -0.0257*** | -0.157*** | -0.468*** | -0.473*** | 99.37% | 91.47% |
| 1998 | -0.00855** | -0.0730** | -0.238*** | -0.240*** | 99.07% | 91.38% |
| 1999 | 0.0221*** | 0.248*** | 0.510*** | 0.519*** | 98.70% | 84.61% |
| 2000 | -0.0619*** | 0.024 | -0.455*** | -0.470*** | 98.37% | 80.28% |
| 2001 | -0.0444*** | 0.0347 | -0.11 | -0.104 | 97.79% | 68.13% |
| 2002 | -0.0478*** | -0.0303 | -0.202*** | -0.212*** | 97.46% | 70.78% |
| 2003 | -0.0663*** | 0.0893*** | -0.454*** | -0.465*** | 97.10% | 81.66% |
| 2004 | -0.0189*** | -0.0256 | -0.225*** | -0.227*** | 96.57% | 86.30% |
| 2005 | 0.00283 | 0.255*** | 0.281*** | 0.285*** | 94.75% | 83.13% |
| 2006 | 0.0334*** | 0.206*** | 0.555*** | 0.568*** | 93.42% | 79.19% |
| 2007 | 0.0462*** | 0.266*** | 0.784*** | 0.811*** | 92.47% | 73.69% |
| 2008 | 0.0288*** | 0.298*** | 0.556*** | 0.566*** | 91.47% | 79.97% |
| 2009 | 0.0154** | 0.177*** | 0.307*** | 0.316*** | 89.82% | 75.78% |

*Note*: p($F01_{t-1} > 0$) denotes percentage of properties having positive primary forest cover in the previous year; p(DF > 0) denotes percentage of properties having positive deforestation.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table 2.6. Testing for Difference Between the Average Effect of Distance

| | (1) Logit WBRE | (4) WBRE | (7) Tobit WBRE-observed dependent variable | (8) Tobit WBRE-latent dependent variable |
|---|---|---|---|---|
| A. Break year: 2004 | | | | |
| $\chi^2$ statistic | 233.690 | 292.100 | 458.910 | 456.140 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Mean of AME between years≤2004 | -0.027 | -0.017 | -0.252 | -0.256 |
| | (0.000) | (0.177) | (0.000) | (0.000) |
| Mean of AME between years>2004 | 0.025 | 0.240 | 0.497 | 0.509 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| B. Break year: 1998 | | | | |
| $\chi^2$statistic | 9.800 | 244.010 | 200.710 | 199.490 |
| | (0.002) | (0.000) | (0.000) | (0.000) |
| Mean of AME between years≤1998 | -0.019 | -0.080 | -0.334 | -0.338 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Mean of AME between years>1998 | -0.008 | 0.140 | 0.141 | 0.144 |
| | (0.028) | (0.000) | (0.000) | (0.000) |
| C. Break year: 1998 and 2004 | | | | |
| $\chi^2$statistic | 241.530 | 361.760 | 470.140 | 469.090 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Mean of AME between years≤1998 | -0.019 | -0.080 | -0.334 | -0.338 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Mean of AME between years>1998 and≤2004 | -0.036 | 0.057 | -0.156 | -0.160 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| Mean of AME between years>2004 | 0.025 | 0.240 | 0.497 | 0.509 |
| | (0.000) | (0.000) | (0.000) | (0.000) |

*Note*: The null hypothesis to be tested is: $\mathrm{Mean}(\mathrm{AME}(\mathrm{IHS}(\mathrm{distance}))_{years\leq breakpoint}) = \mathrm{Mean}(\mathrm{AME}(\mathrm{IHS}(\mathrm{distance}))_{year>breakpoint})$. Wald test is performed, which reports its significance levels using a chi-squared distribution. p-values are in parenthesis. AME denotes average marginal effect.

Table 2.7. Testing for Known Structural Break Point(s) Using an Interrupted Model

| | (1) Logit WBRE | (4) WBRE | (7) Tobit WBRE- observed dependent variable | (8) Tobit WBRE- latent dependent variable |
|---|---|---|---|---|
| A. Break year: 2004 | | | | |
| $\chi^2$ statistic | 231.280 | 133.010 | 237.990 | |
| | (0.000) | (0.000) | (0.000) | |
| AME of IHS(distance), if $year \leq 2004$ | -0.029 | -0.023 | -0.292 | -0.299 |
| | (0.000) | (0.075) | (0.000) | (0.000) |
| AME of IHS(distance), if $year > 2004$ | 0.028 | 0.250 | 0.547 | 0.562 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| B. Break year: 1998 | | | | |
| $\chi^2$ statistic | 631.520 | 439.260 | 829.310 | |
| | (0.000) | (0.000) | (0.000) | |
| AME of IHS(distance), if $year \leq 1998$ | -0.017 | -0.075 | -0.326 | -0.330 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| AME of IHS(distance), if $year > 1998$ | -0.003 | 0.152 | 0.151 | 0.156 |
| | (0.440) | (0.000) | (0.000) | (0.000) |
| C. Break year: 1998 and 2004 | | | | |
| $\chi^2$ statistic | 93.450 | 33.330 | 38.430 | |
| | (0.000) | (0.000) | 0.000 | |
| AME of IHS(distance), if $year \leq 1998$ | -0.018 | -0.074 | -0.331 | -0.334 |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| AME of IHS(distance), if $1998 < year \leq 2004$ | -0.033 | 0.064 | -0.155 | -0.161 |
| | (0.493) | (0.000) | (0.028) | (0.028) |
| AME of IHS(distance), if $year > 2004$ | 0.029 | 0.246 | 0.519 | 0.533 |
| | (0.000) | (0.000) | (0.000) | (0.000) |

*Note*: Using the interrupted models (3 scenarios of breakpoint(s)), Wald test is performed to help determine if there are abrupt changes in both the intercept and the slope of the regression line. The Wald test is computed as chi-squared statistics. p-values are in parenthesis. AME denotes average marginal effect.

Table 2.8. Robustness Check on the Effect of Forest Stock

| | Tobit Model | Two-part Model | | Tobit Model |
|---|---|---|---|---|
| | (9) Tobit WBRE- observed dependent variable | (10) Logit WBRE | (11) WBRE | (12) Tobit WBRE- observed dependent variable |
| 1992 | 0.0004 | -0.017 | 0.035 | -0.291 |
| 1993 | -0.003 | -0.005 | -0.057 | -0.267 |
| 1994 | -0.010*** | -0.003 | -0.126 | -0.178 |
| 1995 | -0.032*** | -0.024* | -0.117 | -0.476* |
| 1996 | -0.001 | -0.015 | 0.077 | -0.208 |
| 1997 | -0.015*** | -0.047*** | -0.273*** | -0.836*** |
| 1998 | -0.013*** | -0.026* | -0.188* | -0.625** |
| 1999 | 0.017*** | 0.040** | 0.192* | 0.603** |
| 2000 | -0.010*** | -0.066*** | -0.065 | -0.663*** |
| 2001 | -0.003 | -0.076** | 0.074 | -0.384 |
| 2002 | -0.006*** | -0.058* | -0.211* | -0.489** |
| 2003 | -0.008*** | -0.075*** | 0.034 | -0.676*** |
| 2004 | -0.016*** | -0.055** | -0.081 | -0.726*** |
| 2005 | 0.012*** | -0.018 | 0.212** | -0.078 |
| 2006 | 0.017*** | 0.006 | 0.057 | 0.136 |
| 2007 | 0.017*** | 0.029 | 0.162 | 0.513** |
| 2008 | 0.027*** | 0.004 | 0.061 | 0.043 |
| 2009 | 0.011*** | -0.030 | -0.033 | -0.272 |
| Dependent variable = loss of forest cover / (forest cover $_{(t-1)}$) | Yes | No | No | No |
| Effect of forest stock in 1km buffer | No | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes |
| Settlement fixed effects | Yes | Yes | Yes | Yes |
| Number of observations | 136,204 | 10,496 | 9,373 | 10,496 |
| Number of groups (properties) | 8,714 | 669 | 669 | 669 |

*Note*: The dependent variable in model (9) is annual loss of forest cover relative to the forest cover in the previous year if it is larger than zero, and it is censoring at both zero and one.

The dependent variable in models in part 1 (10) is 1 if the (IHS -transformed) annual deforested area is larger than zero; the dependent variable in models in part 2 (11) is IHS-transformed annual deforested areas; the dependent variable in Tobit models is IHS-transformed annual deforested areas if the (IHS-transformed) annual deforested area is larger than zero and zero if otherwise.

The regressions (10)-(12) are for properties in the stratified survey sample.

"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table 2.9. Average Marginal Effect of IHS(distance to Ji- Paraná) by Different Years

| | Two-part Model | | Tobit Model |
|---|---|---|---|
| | Part1 | Part2 | |
| | (1) Logit WBRE | (4) WBRE | (7) Tobit WBRE- observed dependent variable |
| 1992 | -0.016* | 0.069 | 0.110 |
| 1993 | 0.009 | 0.320*** | 0.618*** |
| 1994 | -0.007 | 0.127** | 0.196 |
| 1995 | 0.007** | 0.498*** | 0.935*** |
| 1996 | 0.055*** | 0.573*** | 1.429*** |
| 1997 | 0.047*** | 0.390*** | 1.101*** |
| 1998 | 0.036*** | 0.915*** | 1.417*** |
| 1999 | -0.147*** | -0.453*** | -1.590*** |
| 2000 | 0.069*** | 0.610*** | 1.261*** |
| 2001 | 0.326*** | 0.810*** | 3.678*** |
| 2002 | 0.195*** | 1.087*** | 2.606*** |
| 2003 | 0.089*** | 0.653*** | 1.484*** |
| 2004 | 0.070*** | 0.993*** | 1.697*** |
| 2005 | 0.011 | 0.616*** | 0.675*** |
| 2006 | -0.013 | 0.429*** | 0.270* |
| 2007 | -0.056*** | 0.426*** | -0.063 |
| 2008 | -0.098*** | -0.341*** | -1.237*** |
| 2009 | -0.167*** | -0.436*** | -1.755*** |

*Note*: "***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

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# APPENDICES

# Appendix A

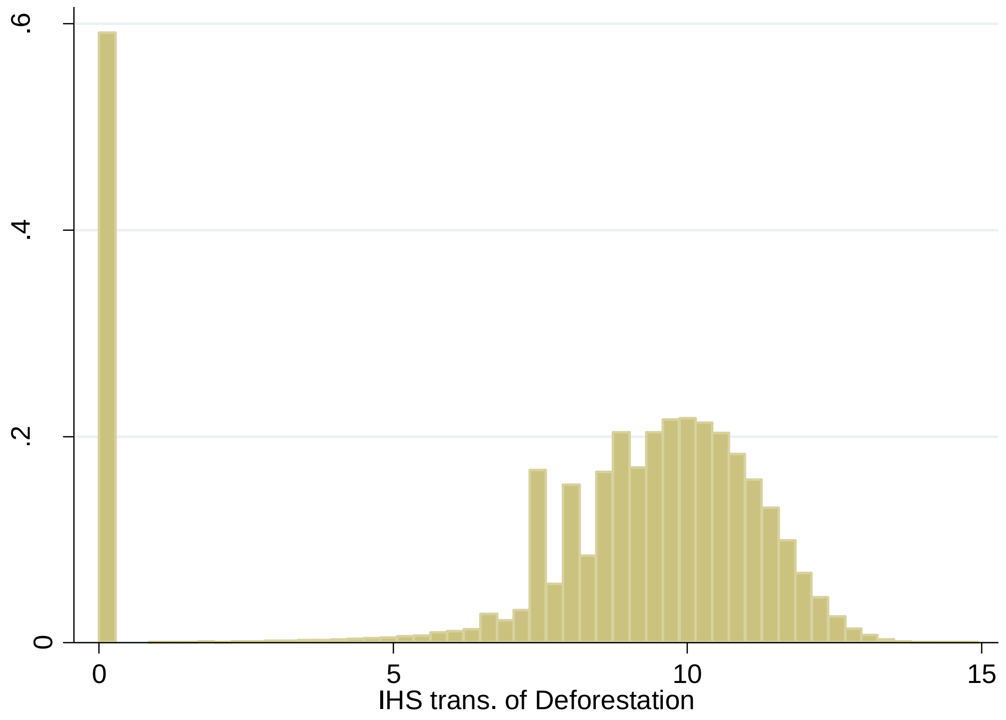

Figure A.2.1. Distribution of IHS transformed dependent variable

# CHAPTER 3: DO FORESTS PROVIDE WATERSHED SERVICES TO LOCAL POPULATIONS IN THE HUMID TROPICS? EVIDENCE FROM THE BRAZILIAN AMAZON

## 1. Introduction

Tropical deforestation affects ecosystem services at multiple scales, from global to local. Key local impacts operate via the effects of deforestation on watershed processes, which include erosion rates, sediment load, water chemistry, total flow, base flow, and groundwater recharge (Gerten 2005; Scanlon et al. 2007; Lele 2009; Willaarts et al. 2012). The effects on river systems in turn affect ecosystem services at both the regional scale—such as fisheries and fluvial transportation—and local scale, such as availability of surface and ground water for livestock and crops immediately downstream (Tegner and Dayton 2000; Pattanayak 2001a–2004). These local watershed services help determine the benefits of agricultural expansion into tropical forests for local populations. To the extent that they are significant, quantifying their value is a necessary first step toward encouraging local policy makers, who have incentives to prioritize economic development over forest conservation (May et al. 2011), to take the benefits of standing forests into account.

Brazil had the world's highest rate of deforestation from 1988 to 2004, averaging 18,400 km$^2$ per year (INPE, 2017). Although its deforestation rate decreased from 27,000 km$^2$ in 2004 to 4.500 km$^2$ in 2012 due to strong government policy enforcement, it is on the rise again and spiked at 7,893 km$^2$ in 2016 (INPE, 2017). The recent increase in deforestation has been attributed to small-scale forest clearing, which may reflect clearing by smallholders (Assunção et al. 2015; Kalamandeen et al. 2018). Little is known about the value of forest watershed services to smallholders in humid tropical regions, such as the Brazilian Amazon, that have relatively flat terrain and abundant water. This is partly because the effects of deforestation on streamflows, including extreme low and high flows, are not fully understood. While compaction of the surface can decrease dry season flow by decreasing recharge, studies in various settings have typically found that deforestation increases flow due to the stronger influence of reduced evapotranspiration (ET) on deforested land (Bosch and Hewlett, 1982; Nóbrega et al., 2017). There is some evidence from our study region to suggest that dry season flow may be lower in large (1,000-100,000 km$^2$) deforested watersheds in the Brazilian Amazon (Rodriguez et al., 2010), but this could also be due to natural variability, since robust time series of streamflow before, during, and after deforestation are not commonly available. In addition to uncertainty about the effects of deforestation on watershed processes, there is little evidence on how changes in those processes affect farm production in the Brazilian Amazon. The scant literature on the impacts of watershed services on agricultural production has focused on crop production in south and southeast Asia (Barkmann et al. 2008; Lele et al. 2008; Pattanayak and Kramer 2001a-b). The relationship between water availability and crop production is very different from the relationship between water availability and livestock production, which is particularly suited to strong annual dry seasons and periodic droughts (Chomitz and Thomas, 2003; Sombroek, 2001).

The impact of deforestation on watershed services is highly context dependent. In terms of hydrological relationships, while deforestation in small watersheds usually increases streamflow, forests also recycle water to the atmosphere through transpiration, so at regional scales deforestation reduces atmospheric moisture cycling and therefore reduces precipitation (Lima et al., 2014). In some parts of the Amazon these effects offset each other, resulting in relatively little change in annual flow (Stickler et al. 2013), but in other parts large impacts of deforestation on moisture recycling dominate, particularly during the dry season and wet-to-dry transition, leading to increases in streamflow (Lima et al. 2014). The impacts of changes in streamflow on farm production are also likely to be nonlinear, in the sense that when water is abundant, increases in streamflow may have little effect or even negative consequences, whereas in conditions of water scarcity where livestock water needs are not being met, or where water sources dry up altogether, small increases in streamflow can have important positive impacts on production. These nonlinearities suggest that the effects of deforestation on watershed services may interact with broader changes in climate. Rainfall decline has been noted in the northern Amazon since the mid-1970s (Malhi et al., 2008); more broadly, across the Amazon Basin, the once-in-a-century 2005 drought was followed by a more severe drought in 2010 (Xu et al., 2011). We therefore estimate the heterogeneous effects of upstream forest cover on downstream agricultural production by watershed size, capturing spatial variation in water abundance, and by year, capturing temporal variation.

Previous studies of watershed services have adopted a three-stage framework that links policy to changes in the ecosystem, which in turn generate changes in ecosystem services, which are valued based on their contribution to profits and utility (Freeman 1993; Pattanayak and Butry 2003; Pattanayak 2004; Ferraro et al. 2011). Thus, the value of forest watershed services is measured as the change in the economic welfare of agricultural households. In our study site, changes in ecosystem services are due to the conversion of forest to pasture, and dairy is the primary agricultural production activity that could be influenced by changes in ecosystem services. We use this approach to estimate whether forests provide valuable watershed services specifically for dairy production downstream (Figure 3.1). This framework for valuation of ecosystem services assumes that the beneficiaries are passive service users. However, in our study region, the farmers who benefit from watershed services also typically own and make land use decisions for part of that watershed. We therefore extend the standard theoretical framework to account for the endogeneity of land use decisions on the property, thus endogenizing forest watershed services. We demonstrate that even with this modification, the marginal value of watershed services is equal to the marginal profits from the services.

In order to estimate how forest watershed services affect milk production and farmer responses, such as changing the dairy cattle stocking rate, we combine data from four sources: (1) socioeconomic data from a four-wave farm household survey over a 14-year span; (2) remote sensing data on the land cover of all farm properties and drainages in the study region over the 14 years; (3) hydrological data, including the full stream network, size of the drainage area for each farm, and monthly precipitation; and (4) spatial data, including property boundaries, road networks, market locations, and biophysical characteristics. This unique dataset allows us to study forest watershed services at the property scale over a long time horizon.

The empirical analysis aims to quantify the marginal effect of forest in the upstream drainage of a given property on downstream land and dairy cattle productivity, stocking density, and milk revenues, while controlling for temporal and spatial fixed effects. We begin by estimating the effect of forest in the upstream drainage but off farm lot, in which watershed services are less likely to be affected by farmers' production and land use decisions. Then we add upstream forest on farm lot to the model and test its endogeneity using two approaches: (1) by testing whether farmers deforest differently in their own drainage versus other areas on their farm, and (2) by performing a Durbin-Wu-Hausman test (augmented regression test) to decide whether the model with upstream forest on farm lot is consistent. Involving and dividing the effects of upstream forest within and outside the farm lot offers informative messages about local beneficiaries and cost-bearers in forest watershed services.

## 2. Theoretical Framework

Environmental economists have demonstrated that the value of forest watershed services can be measured partly as the change in the economic welfare of agricultural households (Pattanayak 2001a). Given forest watershed services that are exogenous to households, Pattanayak (2001a) derived the equivalence of the marginal WTP and the marginal production profits of the watershed service input ($dWTP = d\pi/dW$) under a producer-consumer household utility maximization framework. Following Pattanayak, we start from these same assumptions, but then extend the model to account for the endogeneity of land use and land cover decisions on the lot, thus endogenizing forest watershed services. Below, we demonstrate how watershed services enter a static agricultural household model, then derive the equivalence of the marginal WTP and marginal profits when some of the watershed services are endogenous.

In a static agricultural household model, a household maximizes the utility of consumption of agricultural goods $X$ and leisure $T^l$, conditioned on household characteristics $z^C$ that influence preferences, and subject to the production function, time (labor) constraint, budget constraint, accumulation of agricultural land, and water input resource[25]:

$$\max_{X,T^l,Q,D,I^A} U(X,T^l;z^C) \tag{1}$$

s.t.

$$g(Q,W,L^A,T^A,I^A;z^L) = 0 \tag{2}$$

$$T = T^A + T^l \tag{3}$$

$$P^A X = P^A Q - P^F D - P^I I^A + E \tag{4}$$

$$L^A = \overline{L^A} + D \tag{5}$$

$$W = \overline{W} + W^I = \overline{W} + f(F) \tag{6}$$

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[25] We omit the subscript i for household in the presentation of the model.

The production function of agricultural good $Q$, equation (2), is a function of water input (forest watershed services) $W$, agricultural land input $L^A$, the household's time (labor) devoted to agriculture production $T^A$, and other purchased inputs $I^A$, conditioned on land characteristics $z^L$. In the time (labor) constraint, equation (3), the household allocates its total amount of time $T$ to agricultural production $T^A$ and leisure $T^l$.

In the budget constraint equation (4), the household's total expenses equal to its total income. The household uses its income to consume self-produced agricultural goods $X$ at price $P^A$. The household income source is agricultural product sales and exogenous transfer $E$ (e.g., government welfare payments). The household sells $Q$ amount of agricultural products at price $P^A$, and bears the shadow cost of deforestation[26] and expenses of purchased inputs[27] $P^I I^A$.

The accumulation of agricultural land is illustrated by equation (5). The area of agricultural land $L^A$ owned by the household equals last period's agricultural land $\overline{L^A}$ plus newly deforested areas, $D$.

The drainage (watershed) corresponding to the farm lot can be divided into two parts: drainage within the farm lot and drainage on other lots. Equation (6) represents water input on the lot, determined by watershed services within lot $W^I$ and outside lot $\overline{W}$. Watershed services within the lot is a function of forest cover on the lot, $f(F)$, which would be affected by the household's deforestation decision and therefore is a function of deforestation. We can write deforestation $D$ as a function of watershed services within the lot $W^I$:

$$D = \eta(W^I) \tag{7}$$

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[26] As described in Chapter 2, the shadow cost of deforestation includes the expected monetary amount of the fine for expanding agriculture land beyond the legal amount allowed.

[27] Coincident costs of agricultural production also include own labor on agricultural production. However, wage payments and earning for own labor would cancel out in the budget constraint, and thus for simplicity we only include the cost of purchased inputs and deforestation in the equation.

Substituting (7) into equations (4) and (5), and defining the Lagrangian of the household utility maximum problem, we have:

$$\mathcal{L} = U(X, T^l; z^C) - \varphi g\big(Q, \bar{W} + W^I, \overline{L^A} + \eta(W^I), T^A, I^A; z^L\big)$$

$$+\lambda[P^A Q - P^F \eta(W^I) - P^I I^A + E - P^A X] \tag{8}$$

where $\varphi$ and $\lambda$ are the Lagrange multipliers associated with the production function and the budget constraint. First-order conditions with respect to the choice variables are:

$$\frac{\partial \mathcal{L}}{\partial X} = \frac{\partial U}{\partial X} - \lambda P^A \tag{9}$$

$$\frac{\partial \mathcal{L}}{\partial T^l} = \frac{\partial U}{\partial T^l} + \varphi \frac{\partial g(\cdot)}{\partial T^A} = 0 \tag{10}$$

$$\frac{\partial \mathcal{L}}{\partial Q} = -\varphi \frac{\partial g(\cdot)}{\partial Q} + \lambda P^A = 0 \tag{11}$$

$$\frac{\partial \mathcal{L}}{\partial W^I} = -\varphi \left(\frac{\partial g(\cdot)}{\partial W} \frac{\partial W}{\partial W^I} + \frac{\partial g(\cdot)}{\partial L^A} \frac{\partial \eta(W^I)}{\partial W^I}\right) - \lambda P^F \frac{\partial \eta(W^I)}{\partial W^I} = 0 \tag{12}$$

$$\frac{\partial \mathcal{L}}{\partial I^A} = -\varphi \frac{\partial g(\cdot)}{\partial I^A} - \lambda P^I = 0 \tag{13}$$

Take total differentiation of the Lagrangian with respect to $W^I$ and $E$ while holding utility constant ($dU = 0$):

$$-\varphi \frac{\partial g(\cdot)}{\partial W} \frac{\partial W}{\partial W^I} dW^I - \varphi \frac{\partial g(\cdot)}{\partial L^A} \frac{\partial \eta(W^I)}{\partial W^I} dW^I - \lambda P^F \frac{\partial \eta(W^I)}{\partial W^I} dW^I + \lambda dE = 0. \tag{14}$$

Rewriting equation (14):

$$-\frac{dE}{dW^I} = -\frac{\varphi}{\lambda} \left(\frac{\partial g(\cdot)}{\partial W} \frac{\partial W}{\partial W^I} + \frac{\partial g(\cdot)}{\partial L^A} \frac{\partial \eta(W^I)}{\partial W^I}\right) - P^F \frac{\partial \eta(W^I)}{\partial W^I} \tag{15}$$

If we take total differentiation of the production function with respect to $W^I$, and assuming constant biophysical conditions ($z^L = 0$), we will have:

$$\frac{\partial g(\cdot)}{\partial W} \frac{\partial W}{\partial W^I} + \frac{\partial g(\cdot)}{\partial L^A} \frac{\partial \eta(W^I)}{\partial W^I} = -\frac{\partial g(\cdot)}{\partial Q} \frac{\partial Q}{\partial W^I} - \frac{\partial g(\cdot)}{\partial T^A} \frac{\partial T^A}{\partial W^I} - \frac{\partial g(\cdot)}{\partial I^A} \frac{\partial I^A}{\partial W^I}. \tag{16}$$

Substituting (16) into (15) and rewriting $\frac{\partial g(\cdot)}{\partial Q}$, $\frac{\partial g(\cdot)}{\partial T^A}$, $\frac{\partial g(\cdot)}{\partial I^A}$ based on first-order conditions, we have:

$$-\frac{dE}{dW^I} = P^A \frac{\partial Q}{\partial W^I} - P^F \frac{\partial D}{\partial W^I} - P^I \frac{\partial I^A}{\partial W^I} - \frac{\partial U}{\varphi \partial T^l} \frac{\partial T^A}{\partial W^I} \qquad (17)$$

In the above equation (17), $(-\frac{dE}{dW^I})$ states that the increase in marginal profits from higher $W^I$ is the amount of exogenous income that could be taken away to compensate for the increase in profits. That is, $(-\frac{dE}{dW^I})$ is marginal WTP for watershed services provided within the farm lot. The right-hand side of the equation represents marginal profits[28] from the forest ecosystem services provided within the farm lot, so we have:

$$dWTP^I = \frac{d\pi}{dW^I} \qquad (18)$$

This result demonstrates that when farmers can affect their own forest watershed services, marginal WTP for the forest watershed services within their own land equals to the marginal profits from the services.

## 3. Study Area and Data Description

### 3.1 Study Area

The Ouro Preto do Oeste region of Rondônia is located in northwestern Brazil, in a former frontier region typical of the agrarian settlements the Brazilian government established throughout the Amazon post-1970 (Figure 3.2). During this time period, a federal agency—the National Institute for Colonization and Agrarian Reform (INCRA)—distributed land at little or no cost to new landowners, who were encouraged to migrate from southern and northern eastern states to establish national borders, promote economic development, and alleviate social issues (Moran 1981). Migration to the region continued in the 1980s, motivated by relatively fertile soils and easy access to the region made possible after the BR-364 interstate highway was paved.

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[28] The expenditure on labor is the opportunity cost of family labor's leisure consumption, since we assume the household does not hire outside labor.

The study site was first established as one municipality—Ouro Preto do Oeste, bisected by BR-364—that was subdivided into four, and later six, municipalities that branched out from the highway: Ouro Preto do Oeste, Vale do Paraíso, Urupá, Mirante da Serra, Nova União, and Teixeirópolis. The total population in these six municipalities was more than 83,000 by 2010 (the date of the last census), with an urban population of approximately 54% and the remaining 46% located in rural areas (IBGE 2010). Land tenure is secure and relatively fixed, as expansion into new frontiers is limited in the six municipalities that make up our study region (Jones et al. 1995; Sills and Caviglia-Harris 2009). Thus, farm households have a fixed area of land (which cannot be expanded in the immediate area) with exogenous biophysical characteristics determined by INCRA's original allocation of lots in each settlement.

Major agricultural activities of the region include raising dairy cattle and growing annual (maize, rice, beans, and manioc) and perennial (cacao, coconut, and coffee) crops (Mullan et al. 2017). Income from milk is the both the largest and among the most regular sources of agricultural income. Creating pasture has been the immediate motivation for most deforestation in the Ouro Preto do Oeste region. On average, 46.8% of the land on a property was pasture in 1996, increasing to 77.6% in 2009.

The region's climate is humid tropical, with average temperatures of 24℃ and annual precipitation of 2,300 mm and a distinct dry season from June to September (INPE 2000; Caviglia-Harris et al. 2009; Jiménez-Muñoz et al. 2016). Production conditions differ between wet and dry seasons: Water and grasses are rich in the rainy season, while water inputs are more limited in the dry season, leading to depressed milk productivity (Freifelder et al. 1998; Looper and Waldner 2002; Neal et al. 2011; Zonderland-Thomassen and Ledgard 2012; Doreau et al. 2013).

### 3.2 Data

Data consist of household-level socioeconomic data from a four-wave farm household survey (Caviglia-Harris, Roberts, and Sills 2014); remote sensing land cover data on approximately 9,000 farm properties in the Ouro Preto do Oeste region over the study period (Roberts et al. 2002); hydrological data, including the full stream network, extent and land cover of the drainage area for each farm, access to water sources, and monthly precipitation; and GIS data, including property boundaries, road networks, market locations, and biophysical characteristics. Household survey data include a stratified random sample of households by municipality that were interviewed in the 1996, 2000, 2005, and 2009 dry seasons (Figure 3.2); 196 households were surveyed in 1996, and 195 were surveyed in 2000. Sample size was expanded to 406 in 2005 and 646 in 2009, using the same stratification strategy. The data set used in our analysis includes households that were interviewed in at least two of the four survey waves, resulting in a four-year unbalanced panel[29].

Table 3.1 provides variable definitions and descriptive statistics. The dependent variables are[30]: (1) liters of milk per milk-producing cow in the dry season, (2) liters of milk per milk-producing cow in the wet season, (3) liters of milk per hectare of pasture in the dry season, (4) liters of milk per hectare of pasture in the wet season, (5) head of milk-producing cows per hectare of pasture, (6) milk revenue in the dry season, and (7) milk revenue in the wet season. Data on liters of milk produced and head of milk-producing cows are reported by farm households. Pasture area is measured from the time series of classified Landsat images. Some

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[29] A balanced panel (147 households) was analyzed as well, and estimation results are generally consistent with the unbalanced panel.

[30] In addition to these seven variables, four dependent variables were tested and did not make a difference: head of cattle per hectare of lot, head of milk-producing cows per hectare of lot, liters of milk per hectare of lot in the dry season, and liters of milk per hectare of lot in the wet season.

farm lots have zero milk production and/or zero milk-producing cows in one or both seasons; hence, the dependent variable has a probability mass at zero.

A watershed is defined as “the area of land where all of the water that falls in it and drains off of it goes to a common outlet” (USGS, 2016). Under this definition, a watershed can be small, which includes intermittent drainages (having flowing water periods during wet season but dry during dry season), ephemeral drainages (having flowing water for brief periods in response to rainfall), and even small unchanneled drainages. We use the term “drainage” to indicate all types of watersheds in the following text. The drainage area for each farm lot was identified based on flow direction and the top three flow accumulation points within each surveyed lot using a 1 arc second (30 m) SRTM digital elevation model. Seven properties with watershed size larger than 200 km$^2$ were identified as outliers and excluded from the analysis. Forest cover in these drainages was measured from Landsat images. Figure 3.3 presents land cover in drainages of an example lot.

The output price is milk price in dry and rainy seasons reported by households and adjusted for inflation. Reports on milk prices are missing in the survey for households that reported zero milk production in a given season. To fill in information on missing milk prices, we employ the kriging geostatistical interpolation method to generate farm gate milk price surfaces[31]. The interpolation is based on the premise that the known prices’ “points” and the associated surfaces at nearby locations are more similar to each other than price points at locations distant from each other.

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[31] A Gaussian semivariance model was used in the analysis. For more detailed discussion of geostatistical modeling, see, for example, Cressie (1988), Zimmerman et al. (1999), and Schabenberger and Gotway (2017).

## 4. Empirical Strategy

The empirical analysis aims to quantify the marginal effect of forest in the upstream drainage of a given property on downstream agricultural production. In our study site, changes in ecosystem services are due to the conversion of forest to pasture by individual landowners, and milk is the dominant agricultural production activity that could be influenced by changes in ecosystem services. Therefore, in the following analysis we treat milk as the primary agricultural product on which households make utility and profit optimization decisions. We begin by estimating an output supply function for milk as a function of hydrological and other inputs, while controlling for temporal and spatial fixed effects. The output supply derived from the first-order condition for a maximum profit can be rewritten as a function of output price and input price (Varian 1992). Farm $i$'s milk output in time period $t$, $Q_{it}$, can be represented as:

$$Q_{it} = f(W_{it}, P_{it}, P_{it}^{V}, Z_{it}, \varepsilon_{\mathrm{it}}) \tag{19}$$

where $W_{it}$ represents hydrological inputs (watershed services) for farm $i$ in year $t$, $P_{it}$ is the output price of agricultural product, $P_{it}^{V}$ represents a vector variable of input prices, $Z_{it}$ represents a vector of fixed inputs, and $\varepsilon_{it}$ is the error term.

Empirically, we specify the dependent variable as "milk productivity," which is measured in four ways[32]: (1) liters of milk per milk-producing cow in the dry season, (2) liters of milk per milk-producing cow in the wet season, (3) liters of milk per hectare of pasture in the dry season, and (4) liters of milk per hectare of pasture in the wet season. We also estimate stocking density (head of milk-producing cows per hectare of pasture) as a comparison. Furthermore, we estimate a revenue function of milk to illustrate changes in values, which is a function of all types of

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[32] In addition to these four variables, four more dependent variables were tested and did not make a difference: head of cattle per hectare of lot, head of milk-producing cows per hectare of lot, liters of milk per hectare of lot in the dry season, and liters of milk per hectare of lot in the wet season.

inputs controlling for temporal and spatial fixed effects (Klemick 2011; Gorodnichenko 2012). Farm $i$'s milk revenue in time period $t$, $R_{it}$, can be represented as:

$$R_{it} = f(W_{it}, V_{it}, Z_{it}, \varepsilon_{\mathrm{it}}) \tag{20}$$

where $V_{it}$ is a vector of variable inputs.

Hydrological inputs $W_{it}$ are represented as the size of the area that drains to a given property (upstream drainage size) and the portion of that area covered by mature forest, which are key determinants of streamflow on the farm (Stuckey 2006; Jones et al. 2017). We also include year dummy variables to represent temporal changes in water availability (e.g., rainfall). The main parameter of interest in this paper is the marginal effect of mature forest cover upstream. In estimations of milk productivity and the stocking density of cows, we begin by estimating the marginal effects of forest upstream, which is not interacted with drainage size or year temporal effects, and then we allow for a full set of interaction terms to allow for nonlinear relationships. For interpretation simplicity, we categorize upstream drainage size in two groups, small and large drainages, and create a categorical variable, drainage group. The cutoff point between small and large drainages is the lowest tertile of drainage size, followed by a sensitivity analysis. To fully capture the factors that influence the water intake of cows[33], we also control for accessibility to water sources (main rivers and/or bodies of water).

As demonstrated in the theoretical framework, farmers who benefit from watershed services also typically own and make land use decisions for part of that watershed. We start with an estimation of the effects of upstream forest off lot, which assumes the exogeneity of watershed services. Then we add upstream forests within the farm lot to the model and estimate the two effects in separate terms. Since the area of upstream forests within the household's own

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[33] The water intake of cows would also be influenced by temperature. However, the effect of temperature, which is invariant among farms in the region, will be eliminated in regressions, as we include temporal fixed effects.

lot would be affected by household land use and production decisions, it might be endogenous in the model. We test the endogeneity of upstream forests on lot using two approaches: (1) testing whether farmers deforest differently (e.g. retaining more trees or taking more care with stream crossings) in their own drainage vs. other areas on their farm by using a two-sample $t$-test, which could suggest whether they are aware of and managing for watershed services, and (2) performing a Durbin-Wu-Hausman test for endogeneity in the regression that includes upstream forests on the lot on the right-hand side (Davidson and MacKinnon 1993). If test results suggest the endogeneity of upstream forest on the lot, we use the method of instrumental variables and look for the valid instrumental variable that affects milk production outcome—the dependent variable—only through its effect on the endogenous regressor, areas of upstream forest on lot. However, if test results suggest that upstream forest on the lot is not endogenous in the system, we perform the estimation without an instrumental variable.

Given the constraints on information on variable inputs from the survey and the negative correlation between variable inputs and distance to nearest urban center, we use the distance to nearest urban center as a proxy for input price. In addition, household characteristics are treated as proxies for labor input (quantity and quality), which are determined by average age of household heads, average education level of household heads, and number of household members living on the lot. We use lot characteristics as proxies for fixed inputs, $Z_{it}$, which include soil quality, land slope, size of the property, and age of the property[34]. To control for spatial fixed effects, we also include the dummy variables of municipalities.

Due to the possibility of zero milk production, the dependent variable is semicontinuous. A normal distribution for modeling the data would be inappropriate, because a semicontinuous

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[34] Age of the property is years since first primary forest cleared. For properties that had forest cleared before 1985 (the first year of the study period), ages are assigned based on official settlement records from INCRA.

variable combines a continuous distribution with a point-mass at zero (Olsen and Schafer 2001). Several approaches, such as a censored regression model and two-part model—which have their own advantages and disadvantages (Min and Agresti 2002)—were proposed to account for excess zeros in continuous data. The actual zero outcome values are not our central interest, and we assume that the decision to produce and the level of production are driven by the same processes in our study site. Therefore, we use a censored Tobit model to fit the data.

Our data contain observations over four time periods for the same households, which have the nature of panel data. Fixed effects (FE) and random effects (RE) models are the most common approaches to the panel data problem. No sufficient statistic exists that allows for fixed effects to be conditioned out of the likelihood, and unconditional fixed-effects estimates are biased on the Tobit model (Greene 2004; StataCorp 2015). Hence, we adopt an RE approach and integrate it into a Tobit model. In addition, we use a pooled Tobit model and robust with clustered individual groups, while including dummy variables for year and municipality to control for temporal and spatial correlation in the error term. The unobserved latent dependent variable ${Y_{it}}^*$ is defined as:

$${Y_{it}}^* = \alpha + \beta' X + u_i + e_{it} \tag{21}$$

The observed dependent variable $Y_{it}$ is:

$$Y_{it} = \begin{cases} {Y_{it}}^* & if\ {Y_{it}}^* > 0 \\ 0 & if\ {Y_{it}}^* = 0 \end{cases} \tag{22}$$

where $X = [W_{it}, P_{it}, P_{it}^{V}, Z_{it}]$ is a covariate matrix[35], $u_i$ is an unobserved individual specific time-invariant effect, $e_{it}$ is the remainder disturbance, and $\alpha$ is constant.

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[35] $X = [W_{it}, V_{it}, Z_{it}]$ when estimating the revenue $R_{it}$.

In the regressions, the dependent variable and all explanatory variables with skewed distributions or extreme values are transformed by inverse hyperbolic sine (IHS) [36], except for dummy variables.

## 5. Results

### 5.1 The Effect of Upstream Forest Off Lot

Average marginal effects (AME) on the observed (censored) variable of milk production are reported in Tables 2-5. Given that the effects of explanatory variables may or may not be censored, marginal effects on the expected value for the observed (censored) variable are of central interest, rather than the latent variable (Wooldridge 2002; Greene 2003). In addition to RE Tobit models, we estimate pooled Tobit models with cluster-robust standard errors for comparison. Marginal effects are generally consistent across the different models.

Table 3.2 presents estimates of stocking density of cows and milk productivity, where the effect of mature forest upstream is not interacted with drainage size or year temporal effects. Marginal effects of the proxies for conventional variable inputs generally have expected signs. Among the proxies for labor input, average age of household heads and the number of household members living on the lot are significantly positively related to milk productivity and stocking density. The effect of average education level of the household and the effect of distance to the nearest urban center are insignificant. Among the proxies for fixed input, size of the property has the most substantial influences on milk productivity and stocking density, with a marginal effect

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[36] The inverse hyperbolic sine (IHS) is an alternative transformation approach to handle extreme values that can be defined as negative or zero (Burbidge and Magee 1988):

$$\ln\left(\theta D_{it} + (\theta^2 D_{it}^2 + 1)^{\frac{1}{2}}\right)/\theta = sinh^{-1}(\theta D_{it})/\theta$$

where $\theta = 1$ in our transformation and the inverse sine is approximately equal to $\ln(2D_{it})$, except for small values (e.g., less than 1), so it can be interpreted in the same way as a natural logarithmic transformation (Pence 2006; Friedline et al. 2015).

of -0.71 to -1.65. This negative effect of farm size supports the inverse relationship (IR) between size and productivity, which have been found in a large body of empirical literature (Berry and Cline 1979; Kutcher and Scandizzo 1981; Graeub et al. 2016). The effect of age of the property is significantly positive, which indicates that first-cleared properties have higher productivity levels.

For the primary variable of interest, forest in the drainage off lot is positively related to stocking density (head of cows per hectare of pasture) at a 1% significance level (columns 1 and 2 in Table 3.2), the effects of forest on milk productivity (either liters of milk produced per milk-producing cow or liters of milk per hectare of pasture in dry and rainy seasons) are significant at lower significant levels. For other determinants of watershed services, the area of upstream drainage is negatively related to stocking density at a lower significance level. Negative year dummies suggest that there would have been a significant reduction of milk productivity in the study years. Positive dummy variables on water access support the hypothesis that water is an important input for milk production and raising dairy cattle.

Although the average effects of forest off lot across the years and all sizes of drainages are statistically significantly positive, we find significantly positive effects of upstream forest cover on downstream farm productivity only for farm properties fed by small drainages and in drought years. Table 3.3 presents the marginal effects of forest upstream based on models with the three-way interaction terms of watershed services determinants ( $IHS(forest) \times year\ dummies \times watershed\ group$). The marginal effects of mature forest in the drainage are positive for drainage group 1 in years 2005 and 2009. Drainage group 1 has small drainage areas, which are less than 1.7 km$^2$. Years 2005 and 2009 are drought years, with lower levels of low-flow during the study periods (Figure 3.4). The effect of forest in the dry season is more significant in 2005, which is the driest year. As reported in Table 3.3, for drainage group 1 in year 2005, a 10% increase in forest area in the drainage leads to a 2.05% increase in liters of milk per head of milk-producing cows in the dry season. For year 2009, a 2.38% increase in in liters of milk per head of milk-producing cows in the dry season is expected. Similarly, liters of milk per hectare of pasture in the dry season increase by 2.06% as forest cover upstream increases by 10% for drainage group 1 in year 2005. The positive effect of upstream forest is also reflected in the estimates of stocking density: A 10% increase in forest cover upstream leads to a 1.04% to 1.18% increase in head of cattle per hectare of pasture. In the wet season, when rainfall is abundant, the effect of forest upstream is less significant in 2005, but significant and positive in drainage group 1 and in 2009.

For comparison, we also estimate the alternative specifications on watershed services: interacting forest cover in the drainage area with drainage group and interacting forest cover in the drainage area with dummy variables of year, while controlling for drainage area. As reported in Table 3.4, panel A, when interacting forest with drainage group, the significant positive effect of forest on milk production is for farms fed by small drainages. When interacting forest with year dummies (Table 3.4, panel B), upstream forest has a positive effect on stocking density and milk productivity in in 2000. However, a positive effect of forest in the driest year is less significant.

The marginal effects of forest upstream suggest that in large drainages, or in years when water is relatively abundant, upstream forest cover does not affect downstream farm productivity. However, for farm properties fed by small drainages, the proportion of the drainage with mature forest cover is significantly positively related to milk productivity in drought years. Small drainages are most likely to have ephemeral streams that dry up in the dry season, particularly in drought years. These results suggest that when water is particularly limited, upstream forest cover mitigates that scarcity. Properties with small drainages are more vulnerable to reductions in hydrological inputs in the dry season, and therefore are more sensitive to changes in ecosystem services.

To measure the value of forest watershed services, we further estimate milk revenue function. Consistent with the estimates of milk productivity, for farm properties with small drainages, the marginal effects of forest upstream on milk revenue are significantly positive in the dry season of year 2005. As reported in Table 3.5, panel D, column 1, a 10% increase in forest cover upstream off lot leads to 1.89% - 2.18% increase in milk revenue in dry season. That is, for properties with small drainages, if the forest cover upstream off lot had increased from 2.77 $km^2$ to 3.05 $km^2$, single-family milk revenue in the dry season would have been R\$26-R\$48 higher in a drought year.

### 5.2 The Effect of Upstream Forest on Lot

We start with tests on the endogeneity of upstream forest on lot. Table 3.6 reports two-sample *t*-test results on the equality between percentage of forest on the lot within drainages and percentage of forest on the lot outside drainages. Under the null hypothesis that “difference=0”, the *p*-value is greater than 0.05, so we cannot reject the null and conclude that the difference in means is not statistically significantly different from 0. That is, percentage of forest cover on the lot within drainages and outside drainages are not significantly different from each other. This suggests that households did not deforest differently. In the Durbin-Wu-Hausman test on endogeneity, the coefficient of the residuals of the potential endogenous variable, upstream forest on lot, is not significantly different from zero in the augmented regression (Table 3.7). This suggests there is no evidence of endogeneity of upstream forest on lot.

Since both tests on endogeneity suggest that upstream forest on lot is not endogenous in the system, without instrumental variables, regressions on upstream forest on lot are consistent. Table 3.8 presents the estimates of milk production, where the effects of mature forest upstream off lot and on lot are not interacted with drainage size or year temporal effects. The effect of upstream forest off lot is still significantly positively related to milk production across different models, and the exception is the effect on milk produced per cow in the dry season. However, the effect of upstream forest on lot is insignificant across different models. Other control variables on drainage size, water access, land, and household characteristics have the same effects as in regressions on upstream forest purely off lot.

Table 3.9 presents the marginal effects of forest upstream off lot and on lot based on models with the three-way interaction terms of watershed services determinants: $IHS(forest\ off\ lot) \times year\ dummies \times watershed\ group),\ IHS(forest\ on\ lot) \times year\ dummies \times watershed\ group)$. We obtain similar results for upstream forest off lot: significantly positive effects of upstream forest on milk production in drought years and small drainages. However, the effects of upstream forest on lot are negative in small drainages and drought years, and they are statistically significant in small drainages and year 2009. In addition, except for 1996, upstream forest on lot in large drainages has significantly positive effects on milk production.

These results suggest that upstream forest on lot has mixed effects on downstream milk production. When groups are pooled, the effects of forest on lot on milk production when water is scarce can be washed out. Regulating water quantity, therefore, is not the only mechanism between the effects of upstream forest on lot and downstream milk production.

## 6. Robustness Checks

### 6.1 Effects of Small Drainages

A possible alternative explanation for why forest cover in small drainages influences downstream production is that these forests are closer to the property. More generally, our estimated relationship could just reflect spatial correlations between neighboring properties. We rule these out by testing the effect of forest cover in a 1 km buffer around the lot and comparing it with the estimated effect in small drainages (Table 3.10). Results suggest that forest cover in the buffer does not have as large or statistically significant an effect as forest in small drainages and drought years. This supports the interpretation that the positive relationship between forests and farm productivity when water is scarce is driven by hydrological processes rather than other influences of forest or spatial correlation between properties.

### 6.2 Cutoff Points of "Small" Drainage

We further test how marginal effects of upstream forest on milk production respond to changes in the small drainage cutoff points. Figure 3.5 reports the marginal effects of upstream forest in year 2005 and small drainages. The magnitudes of the marginal effects of upstream forest in small drainages are generally decreasing with the higher small drainage cutoff points. The statistically significant effect of upstream forest holds as long as we treat drainages smaller than 1.7 $km^2$ as "small."

### 6.3 Lagged Effects of Upstream Forest

The effect of forest harvesting on water runoff might have time-lag (Zhang et al. 2012). We therefore test the lagged effect of upstream forest (Table 3.11). Both the lagged effects of upstream forest off lot and on lot are insignificant across different models. Results suggest that there is no statistically significant lagged effect of forest on milk production in our study region.

## 7. Discussion and Conclusions

The study, which examines local watershed services from forests in the humid tropics, not only contributes to the literature that measures the economic benefits of forest conservation at the local scale, but also provides evidence on the effects of deforestation on agricultural production as the climate changes. Empirical analysis suggests that in large drainages, or in years when rainfall is relatively abundant, upstream forest cover off farm lot does not affect the land use intensity or productivity of downstream dairy production. However, for farm properties fed by small drainages, the proportion of the drainage with mature forest cover off lot is significantly positively related to both milk production per cow and the stocking rate of cows per hectare of pasture in the dry season of drought years. The effects of upstream mature forest cover on lot are not endogenous in the milk production system, and they exhibit mixed effects on downstream milk production.

The increased frequency of historically rare droughts in the Amazon has raised concerns about impacts on fluvial transportation, forest flammability, and regional carbon balance with feedback to climate change (Malhi et al. 2008; Philips et al. 2009; Lewis et al. 2011; Marengo et al. 2013). Although the causes of the 2005 drought and future scenarios may differ (Zeng et al. 2008), the findings in this paper demonstrate direct negative impacts on downstream farmers, especially in deforested regions. Thus, conserving forest cover in drainages that supply farms could enhance their resilience to climatic extremes. This suggests that even in this relatively flat, humid tropical region, forests provide a form of insurance against extreme weather. This insurance function is likely to become more important in the future, as rainfall in the region becomes more variable with global climate change (Zeng et al. 2008; Malhi et al. 2009). These findings should encourage consideration of the benefits of standing forest when designing regional and local land use policy.

The finding that standing forest on others' farm lots provides insurance against drought raises the possibility that individual farmers could negotiate with and/or subsidize upstream neighbors by retaining forest in the parts of the drainage that lie outside their own property. Farmers are neither pure beneficiaries nor cost bearers in forest watershed services.

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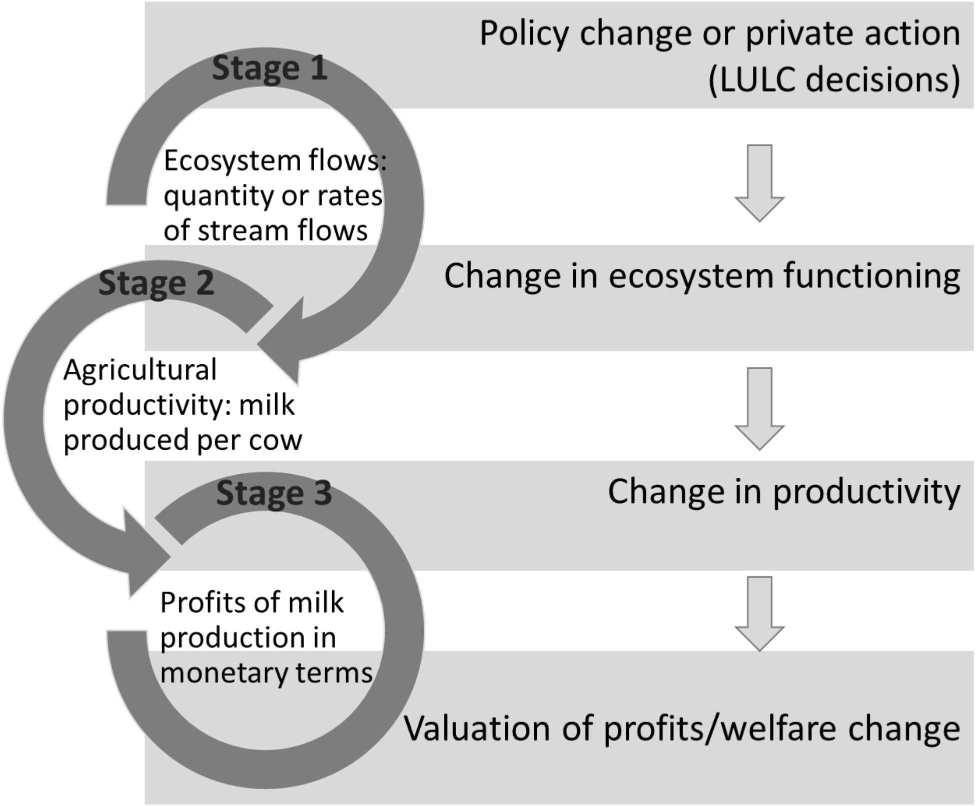

Figure 3.1. The three-stage framework of forest watershed services

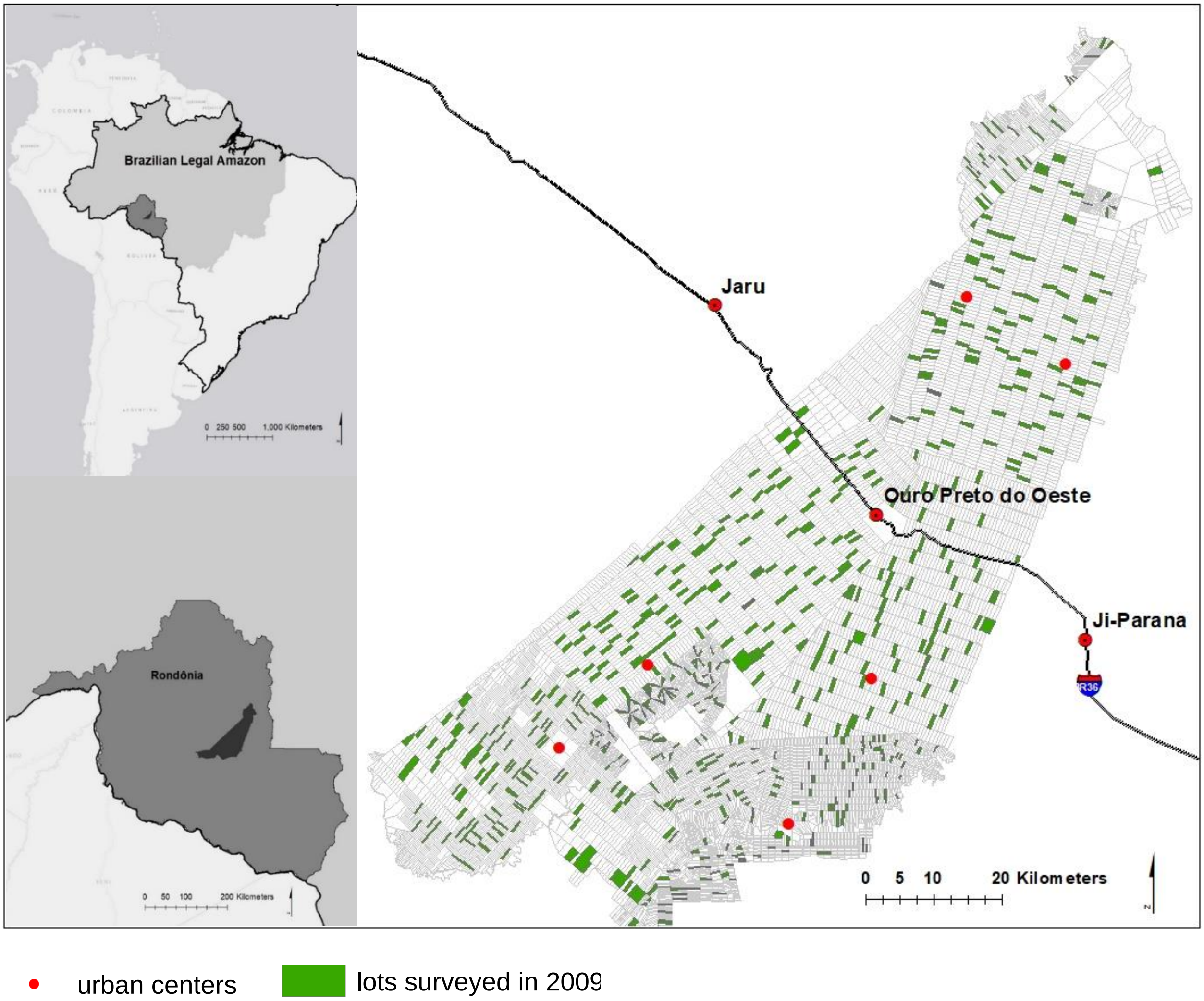

Figure 3.2. Study area and landholdings of interviewed households

*Note:* The 2009 lots include all of the lots originally sampled in 1996, a sample of residents who had moved off those lots, and samples of households in agrarian reform settlements established since 1996.

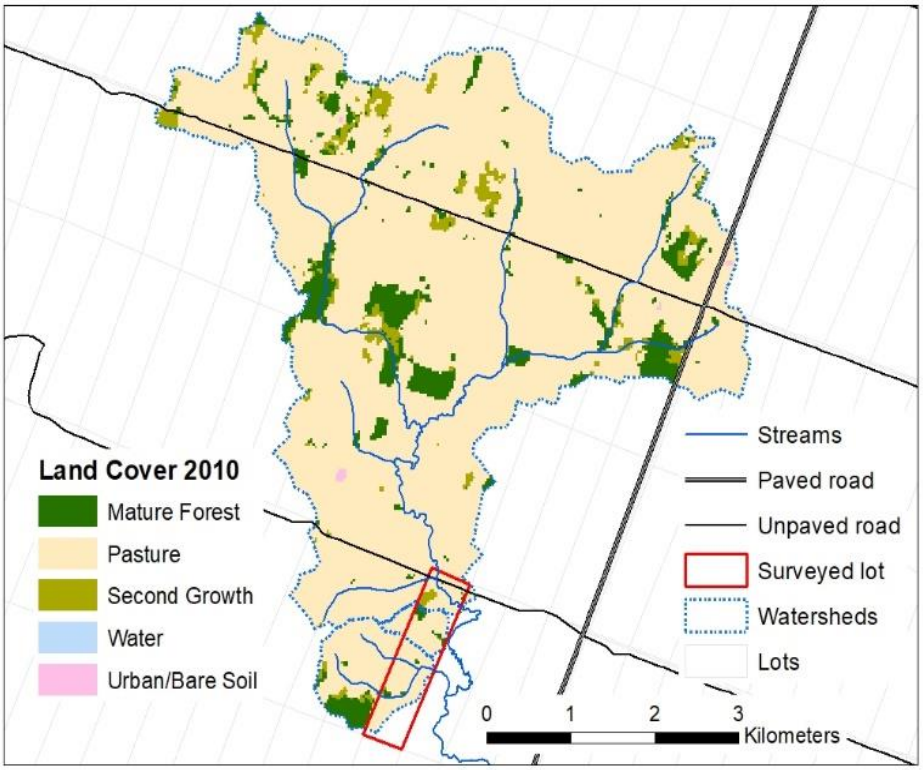

Figure 3.3. Land Cover in Watersheds of An Example Lot

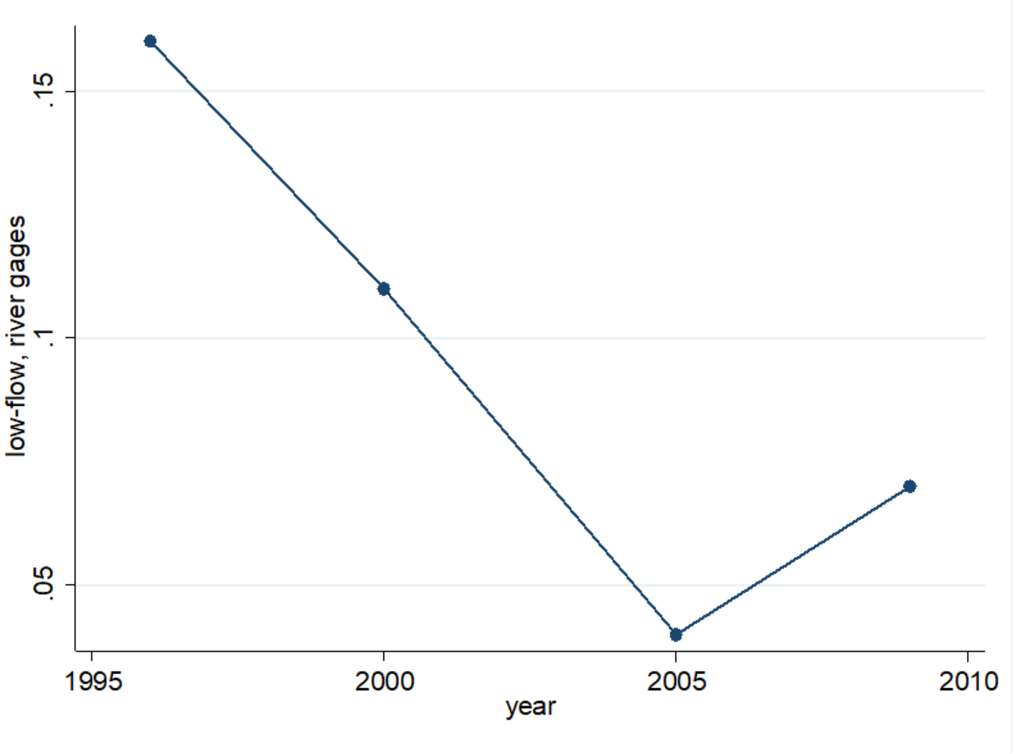

Figure 3.4. Low-flow at River Gages ($m^3$/day)

*Notes:* Low-flow is the mean of the 10% lowest stream flow for each survey year at two watersheds in the study area (Jaru River and Jamari River).

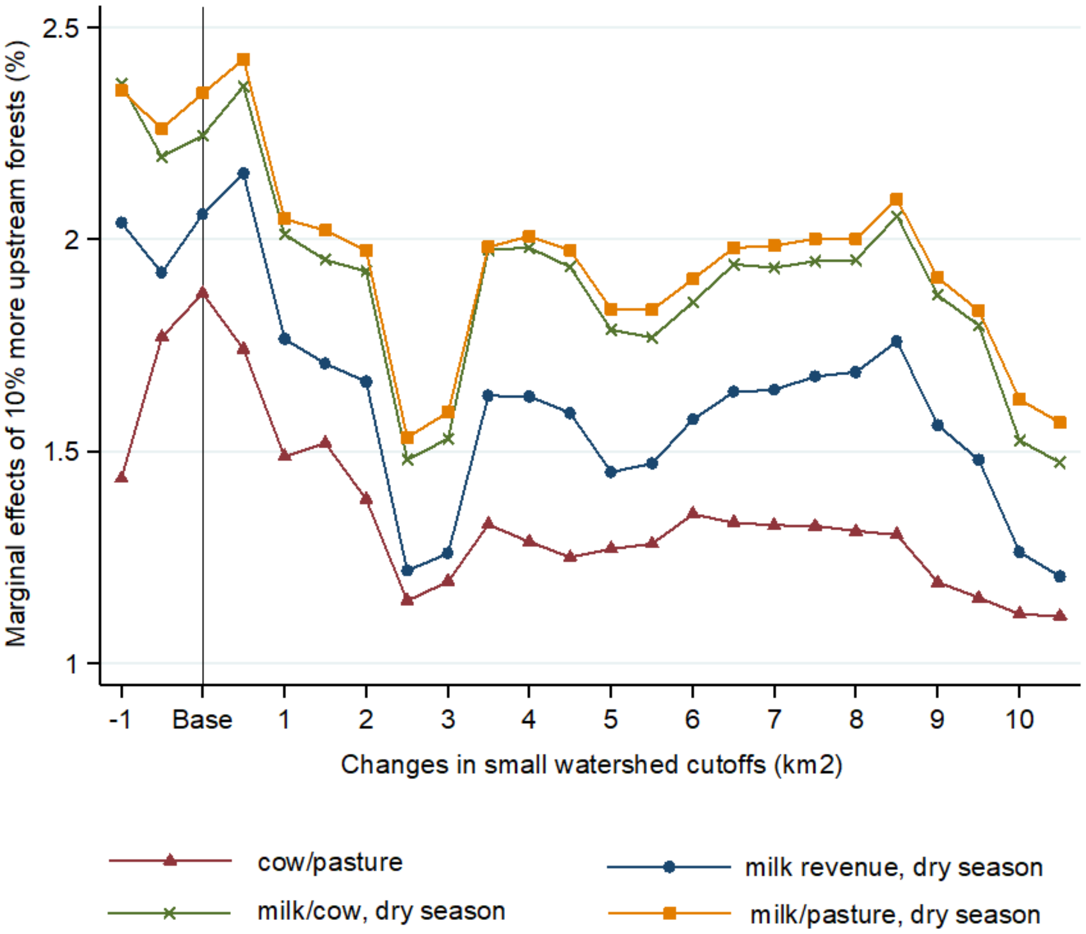

Figure 3.5. Sensitivity Analysis of Small Watershed Cutoffs

*Notes:* The base point of small watershed cutoff is the lowest tertile of watershed size, 1.7 $km^2$. Marginal effects reported in the figure are for year 2005 and small watersheds.

Table 3.1. Descriptive Statistics

| | **Definition** | **1996** | **2000** | **2005** | **2009** |
|---|---|---|---|---|---|
| **Dependent Variables** | | | | | |
| milk/cow, dry | liters of milk per cow in dry season | 2.49 | 2.69 | 1.94 | 2.78 |
| | | (2.45) | (1.81) | (2.53) | (3.13) |
| milk/cow, wet | liters of milk per cow in wet season | 3.67 | 3.66 | 3.30 | 4.78 |
| | | (3.98) | (2.68) | (3.05) | (7.06) |
| milk/pasture, dry | liters of milk per hectare of pasture in dry season | 0.90 | 1.23 | 1.18 | 1.27 |
| | | (0.96) | (1.40) | (2.02) | (1.77) |
| milk/pasture, wet | liters of milk per hectare of pasture in wet season | 1.32 | 1.61 | 2.04 | 2.02 |
| | | (1.50) | (1.74) | (3.52) | (2.75) |
| cattle/pasture | head of cattle per hectare of pasture | 37.23 | 38.31 | 64.82 | 38.82 |
| | | (39.29) | (38.91) | (101.68) | (39.67) |
| milk revenue, dry | milk revenue in dry season, R$2000 | 879.54 | 2087.87 | 1367.29 | 2220.02 |
| | | (1010.71) | (2578.12) | (1810.12) | (3020.36) |
| milk revenue, wet | milk revenue in wet season, R$2000 | 1329.36 | 1957.45 | 2478.88 | 2824.30 |
| | | (1641.25) | (2398.50) | (3083.75) | (3928.91) |
| **Hydrologic Variables** | | | | | |
| watershed area | total watershed areas of the lot, km$^2$ | 14.60 | 13.80 | 14.00 | 13.40 |
| | | (32.40) | (32.00) | (29.80) | (28.70) |
| watershed group | categorical variable; =1 for small watershed, =2 large watershed; the cutoff point between small and large watersheds is the lowest tertile of watershed size | 1.69 | 1.68 | 1.66 | 1.65 |
| | | (0.46) | (0.47) | (0.47) | (0.48) |
| forest | total area of upstream primary forest, km$^2$ | 5.31 | 3.76 | 2.84 | 2.06 |
| | | (14.30) | (11.60) | (7.92) | (4.96) |
| forest off lot | area of upstream primary forest off the lot, km$^2$ | 5.15 | 3.66 | 2.77 | 2.01 |
| | | (14.29) | (11.59) | (7.91) | (4.95) |
| water access | dummy; =1 for properties with access to rivers and streams, 0 otherwise | 0.35 | 0.33 | 0.32 | 0.30 |
| | | (0.48) | (0.47) | (0.47) | (0.46) |
| **Output Prices** | | | | | |
| milk price, dry | farm gate per liter price of milk in the dry season, replaced with kring milk price when missing, R$2000 | 0.19 | 0.27 | 0.25 | 0.29 |
| | | (0.02) | (0.04) | (0.04) | (0.06) |
| milk price, wet | farm gate per liter price of milk in the wet season, replaced with kring milk price when missing, R$2000 | 0.19 | 0.19 | 0.26 | 0.23 |
| | | (0.02) | (0.05) | (0.04) | (0.04) |
| **Proxies for Inputs** | | | | | |
| distance | distance by road to closest urban center, meters | 15009.51 | 15039.80 | 15287.98 | 15260.30 |
| | | (6882.73) | (6806.63) | (7194.35) | (7230.29) |
| household age | average age of the household heads, years | 44.85 | 47.35 | 47.20 | 50.43 |
| | | (13.30) | (12.54) | (14.08) | (14.07) |
| household education | average education level of the household heads, years | 2.64 | 2.73 | 3.20 | 3.49 |
| | | (2.46) | (1.79) | (2.15) | (2.69) |
| households | number of household members living on the lot | 8.65 | 7.18 | 5.61 | 5.11 |
| | | (6.02) | (5.80) | (3.58) | (3.41) |
| soil | percentage of lot characterized as good soil | 0.03 | 0.02 | 0.02 | 0.02 |
| | | (0.16) | (0.13) | (0.14) | (0.14) |
| slope | weighted average of lot slope, (0-50%) | 4.06 | 4.08 | 4.04 | 4.04 |
| | | (1.85) | (1.85) | (1.84) | (1.84) |
| lot size | lot size, hectares | 79.41 | 78.17 | 69.48 | 68.98 |
| | | (39.45) | (40.00) | (40.48) | (40.59) |
| lot age | age of the property, years | 19.35 | 22.93 | 25.36 | 29.28 |
| | | (8.75) | (9.09) | (10.78) | (10.75) |
| **Observations** | | 176 | 177 | 293 | 291 |

Table 3.2. Marginal Effects of Upstream Forest Off Lot: No Interaction Terms

| | **IHS(cow/pasture)** | | **IHS(milk/cow), dry** | | **IHS(milk/cow), wet** | | **IHS(milk/pasture),dry** | | **IHS(milk/pasture),wet** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit |
| IHS(forest off lot) | 0.098*** | 0.090** | 0.151* | 0.154* | 0.176** | 0.169** | 0.147** | 0.145* | 0.171** | 0.160** |
| | (0.036) | (0.039) | (0.078) | (0.084) | (0.079) | (0.082) | (0.071) | (0.075) | (0.072) | (0.074) |
| y2000 | -0.417* | -0.408* | -1.379*** | -1.380*** | -1.558*** | -1.562*** | -1.150*** | -1.162*** | -1.183*** | -1.189*** |
| | (0.219) | (0.218) | (0.464) | (0.467) | (0.417) | (0.447) | (0.414) | (0.420) | (0.376) | (0.402) |
| y2005 | 0.005 | 0.044 | -2.223*** | -2.143*** | -1.930*** | -1.887*** | -1.752*** | -1.680*** | -1.452*** | -1.434*** |
| | (0.225) | (0.232) | (0.481) | (0.490) | (0.523) | (0.516) | (0.434) | (0.445) | (0.474) | (0.473) |
| y2009 | -0.715** | -0.657** | -1.845*** | -1.733*** | -2.182*** | -2.097*** | -1.706*** | -1.604*** | -1.868*** | -1.802*** |
| | (0.289) | (0.287) | (0.620) | (0.628) | (0.569) | (0.578) | (0.560) | (0.565) | (0.517) | (0.522) |
| IHS(watershed) | -0.173** | -0.148** | -0.264 | -0.251 | -0.333* | -0.312* | -0.233 | -0.213 | -0.290* | -0.263* |
| | (0.079) | (0.074) | (0.171) | (0.159) | (0.173) | (0.160) | (0.157) | (0.142) | (0.158) | (0.143) |
| water access | 0.300* | 0.280* | 0.547 | 0.523* | 0.579 | 0.530* | 0.543 | 0.526* | 0.551 | 0.514* |
| | (0.180) | (0.143) | (0.390) | (0.311) | (0.396) | (0.319) | (0.360) | (0.279) | (0.363) | (0.288) |
| milk price | 2.182 | 2.041* | 2.709 | 2.624 | -0.322 | 0.496 | 4.035 | 4.046* | 0.802 | 1.864 |
| | (1.385) | (1.197) | (2.938) | (2.358) | (3.396) | (2.623) | (2.630) | (2.175) | (3.067) | (2.386) |
| IHS(distance) | 0.177 | 0.126 | -0.118 | -0.178 | -0.022 | -0.079 | -0.002 | -0.075 | 0.066 | -0.002 |
| | (0.153) | (0.145) | (0.332) | (0.305) | (0.336) | (0.312) | (0.306) | (0.273) | (0.308) | (0.280) |
| household age | 0.020*** | 0.018*** | 0.036*** | 0.032** | 0.038*** | 0.034** | 0.035*** | 0.032*** | 0.037*** | 0.034*** |
| | (0.006) | (0.006) | (0.012) | (0.013) | (0.012) | (0.013) | (0.011) | (0.012) | (0.011) | (0.012) |
| household edu | -0.002 | 0.007 | -0.035 | -0.045 | -0.003 | -0.007 | -0.016 | -0.018 | 0.011 | 0.016 |
| | (0.032) | (0.034) | (0.068) | (0.072) | (0.069) | (0.074) | (0.061) | (0.065) | (0.063) | (0.067) |
| family | 0.045*** | 0.057*** | 0.077** | 0.104*** | 0.081** | 0.111*** | 0.065** | 0.094*** | 0.071** | 0.100*** |
| | (0.014) | (0.014) | (0.031) | (0.034) | (0.032) | (0.035) | (0.028) | (0.030) | (0.029) | (0.032) |
| soil | 0.173 | 0.229 | 0.296 | 0.330 | 0.494 | 0.524 | 0.285 | 0.366 | 0.495 | 0.573 |
| | (0.558) | (0.388) | (1.205) | (0.702) | (1.227) | (0.750) | (1.112) | (0.632) | (1.123) | (0.680) |
| IHS(slope) | 0.027 | 0.097 | -0.200 | -0.116 | -0.193 | -0.173 | 0.004 | 0.113 | 0.036 | 0.080 |
| | (0.256) | (0.227) | (0.556) | (0.483) | (0.565) | (0.505) | (0.513) | (0.441) | (0.517) | (0.459) |

Table 3.2. (continued)

| | **IHS(cow/pasture)** | | **IHS(milk/cow), dry** | | **IHS(milk/cow), wet** | | **IHS(milk/pasture),dry** | | **IHS(milk/pasture),wet** | |
|---|---|---|---|---|---|---|---|---|---|---|
| IHS(lot size) | -0.731*** | -0.708*** | -0.705* | -0.650 | -1.501*** | -1.413*** | -0.938** | -0.891** | -1.650*** | -1.575*** |
| | (0.196) | (0.187) | (0.429) | (0.435) | (0.433) | (0.416) | (0.393) | (0.398) | (0.395) | (0.379) |
| lot age | 0.019 | 0.017 | 0.072** | 0.072** | 0.107*** | 0.107*** | 0.067** | 0.065** | 0.098*** | 0.097*** |
| | (0.014) | (0.013) | (0.030) | (0.031) | (0.030) | (0.030) | (0.027) | (0.029) | (0.028) | (0.028) |
| Municipality (spatial) fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Number of observations | 933 | 933 | 933 | 933 | 933 | 933 | 933 | 933 | 933 | 933 |

*Note*: These are average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable. The first row indicates five specifications on the dependent variable.

In the regression of lHS(cow/pasture), “milk price” represent the average values for dry and rainy seasons. In the regression of lHS(milk/cow), dry and IHS(milk/pasture), dry, “milk price” represent values in the dry season. In the regression of lHS(milk/cow), wet and IHS(milk/pasture), wet, “milk price” represent values in the wet season.

Standard errors in parentheses.

“***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

Table 3.3. Marginal Effects of Upstream Forest off Lot: A Full Set of Interactions

| | **IHS(cow/pasture)** | | **IHS(milk/cow), dry** | | **IHS(milk/cow), wet** | | **IHS(milk/pasture),dry** | | **IHS(milk/pasture),wet** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit |
| IHS(forest off lot) by year and watershed group | | | | | | | | | | |
| 1996 1 | -0.012 | 0.023 | -0.227 | -0.136 | -0.204 | -0.135 | -0.141 | -0.049 | -0.114 | -0.044 |
| | (0.095) | (0.073) | (0.208) | (0.121) | (0.213) | (0.138) | (0.186) | (0.106) | (0.191) | (0.123) |
| 1996 2 | -0.172 | -0.166 | -0.373 | -0.348 | -0.28 | -0.268 | -0.326 | -0.317 | -0.25 | -0.253 |
| | (0.155) | (0.14) | (0.343) | (0.278) | (0.348) | (0.283) | (0.309) | (0.248) | (0.314) | (0.254) |
| 2000 1 | 0.102 | 0.088 | 0.116 | 0.114 | 0.134 | 0.135 | 0.1 | 0.083 | 0.114 | 0.102 |
| | (0.067) | (0.099) | (0.14) | (0.193) | (0.142) | (0.2) | (0.126) | (0.176) | (0.129) | (0.182) |
| 2000 2 | -0.142 | -0.132 | -0.174 | -0.142 | -0.045 | -0.02 | -0.154 | -0.137 | -0.052 | -0.041 |
| | (0.146) | (0.139) | (0.321) | (0.309) | (0.325) | (0.319) | (0.291) | (0.279) | (0.294) | (0.289) |
| 2005 1 | 0.118** | 0.104* | 0.205** | 0.192 | 0.186* | 0.172 | 0.206** | 0.188 | 0.190* | 0.173 |
| | (0.052) | (0.057) | (0.105) | (0.138) | (0.111) | (0.12) | (0.096) | (0.129) | (0.101) | (0.111) |
| 2005 2 | -0.164 | -0.164 | -0.275 | -0.249 | -0.326 | -0.292 | -0.256 | -0.239 | -0.305 | -0.284 |
| | (0.123) | (0.108) | (0.258) | (0.214) | (0.265) | (0.22) | (0.235) | (0.197) | (0.242) | (0.204) |
| 2009 1 | 0.141*** | 0.125* | 0.238** | 0.242* | 0.320*** | 0.305** | 0.221** | 0.216* | 0.294*** | 0.271** |
| | (0.052) | (0.071) | (0.113) | (0.131) | (0.113) | (0.136) | (0.102) | (0.121) | (0.103) | (0.126) |
| 2009 2 | -0.079 | -0.073 | -0.33 | -0.281 | -0.283 | -0.231 | -0.26 | -0.223 | -0.221 | -0.185 |
| | (0.12) | (0.11) | (0.262) | (0.237) | (0.267) | (0.245) | (0.237) | (0.211) | (0.242) | (0.22) |

*Note*: These are average marginal effects (average of individual marginal effects) of his-transformed mature forest cover upstream on the observed (censored) dependent variable.

Standard errors in parentheses;

"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table 3.4. Alternative Regressions on Upstream Forest off Lot

| | **IHS(cow/pasture)** | | **IHS(milk/cow), dry** | | **IHS(milk/cow), wet** | | **IHS(milk/pasture),dry** | | **IHS(milk/pasture),wet** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit |
| A. watershed group* IHS(forest off lot) | | | | | | | | | | |
| IHS(forest off lot) by watershed group | | | | | | | | | | |
| 1 | 0.104*** | 0.095** | 0.157* | 0.157* | 0.183** | 0.175** | 0.153** | 0.148** | 0.177** | 0.165** |
| | (0.036) | (0.04) | (0.078) | (0.083) | (0.079) | (0.082) | (0.071) | (0.076) | (0.072) | (0.074) |
| 2 | -0.056 | -0.069 | -0.158 | -0.156 | -0.15 | -0.136 | -0.116 | -0.132 | -0.115 | -0.12 |
| | (0.107) | (0.09) | (0.232) | (0.195) | (0.236) | (0.2) | (0.211) | (0.175) | (0.214) | (0.181) |
| B. year*IHS(forest off lot) | | | | | | | | | | |
| IHS(forest off lot) by year | | | | | | | | | | |
| 1996 | 0.084 | 0.095* | -0.004 | 0.037 | 0.043 | 0.059 | 0.038 | 0.073 | 0.085 | 0.097 |
| | (0.066) | (0.05) | (0.145) | (0.103) | (0.147) | (0.103) | (0.13) | (0.089) | (0.133) | (0.09) |
| 2000 | 0.167*** | 0.164** | 0.297*** | 0.310** | 0.353*** | 0.360** | 0.274*** | 0.276** | 0.325*** | 0.322** |
| | (0.053) | (0.071) | (0.114) | (0.147) | (0.116) | (0.152) | (0.103) | (0.134) | (0.105) | (0.139) |
| 2005 | 0.078* | 0.065 | 0.183** | 0.178* | 0.128 | 0.116 | 0.178** | 0.169* | 0.13 | 0.116 |
| | (0.043) | (0.046) | (0.09) | (0.107) | (0.092) | (0.096) | (0.082) | (0.098) | (0.084) | (0.088) |
| 2009 | 0.091** | 0.079 | 0.062 | 0.068 | 0.154* | 0.146 | 0.065 | 0.066 | 0.148* | 0.135 |
| | (0.042) | (0.052) | (0.092) | (0.103) | (0.093) | (0.106) | (0.083) | (0.094) | (0.085) | (0.096) |

*Note*: These are average marginal effects (average of individual marginal effects) of IHS-transformed mature forest cover upstream on the observed (censored) dependent variable.

Standard errors in parentheses;

"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table 3.5. Marginal Effects of Forest off Lot on Revenue

| | milk revenue, dry | | milk revenue, wet | | total milk revenue | |
|---|---|---|---|---|---|---|
| | **RE Tobit** | **Pooled Tobit** | **RE Tobit** | **Pooled Tobit** | **RE Tobit** | **Pooled Tobit** |
| A. no interaction | | | | | | |
| IHS(forest off lot) | 0.141* | 0.142* | 0.156** | 0.150** | 0.156** | 0.147* |
| | (0.073) | (0.075) | (0.073) | (0.073) | (0.077) | (0.077) |
| B. watershed group* IHS(forest off lot) | | | | | | |
| IHS(forest off lot) by watershed group | | | | | | |
| 1 | 0.142** | 0.140* | 0.159** | 0.151** | 0.161** | 0.149* |
| | (0.071) | (0.074) | (0.072) | (0.073) | (0.076) | (0.077) |
| 2 | -0.152 | -0.168 | -0.142 | -0.146 | -0.127 | -0.146 |
| | (0.217) | (0.179) | (0.218) | (0.180) | (0.229) | (0.190) |
| C. year*IHS(forest off lot) | | | | | | |
| IHS(forest off lot) by year | | | | | | |
| 1996 | 0.053 | 0.095 | 0.096 | 0.119 | 0.081 | 0.109 |
| | (0.130) | (0.087) | (0.132) | (0.087) | (0.139) | (0.091) |
| 2000 | 0.273*** | 0.282** | 0.310*** | 0.316** | 0.326*** | 0.330** |
| | (0.106) | (0.136) | (0.105) | (0.136) | (0.111) | (0.146) |
| 2005 | 0.160* | 0.152 | 0.105 | 0.092 | 0.128 | 0.109 |
| | (0.083) | (0.098) | (0.085) | (0.089) | (0.090) | (0.094) |
| 2009 | 0.069 | 0.070 | 0.143 | 0.132 | 0.115 | 0.101 |
| | (0.085) | (0.093) | (0.085) | (0.094) | (0.090) | (0.100) |
| D. year*watershed group*IHS(forest off lot) | | | | | | |
| IHS(forest off lot) by year and watershed group | | | | | | |
| 1996 1 | -0.150 | -0.053 | -0.134 | -0.052 | -0.149 | -0.066 |
| | (0.183) | (0.094) | (0.187) | (0.111) | (0.198) | (0.114) |
| 1996 2 | -0.366 | -0.351 | -0.287 | -0.286 | -0.329 | -0.328 |
| | (0.313) | (0.249) | (0.315) | (0.253) | (0.331) | (0.267) |
| 2000 1 | 0.105 | 0.094 | 0.116 | 0.110 | 0.123 | 0.114 |
| | (0.127) | (0.176) | (0.127) | (0.176) | (0.135) | (0.191) |
| 2000 2 | -0.215 | -0.191 | -0.092 | -0.079 | -0.152 | -0.143 |
| | (0.299) | (0.292) | (0.297) | (0.291) | (0.314) | (0.310) |

Table 3.5. (continued)

| | **milk revenue, dry** | | **milk revenue, wet** | | **total milk revenue** | |
|---|---|---|---|---|---|---|
| | **RE Tobit** | **Pooled Tobit** | **RE Tobit** | **Pooled Tobit** | **RE Tobit** | **Pooled Tobit** |
| 2005 1 | 0.189** | 0.173 | 0.166** | 0.149 | 0.182* | 0.160 |
| | (0.096) | (0.125) | (0.101) | (0.111) | (0.106) | (0.117) |
| 2005 2 | -0.313 | -0.295 | -0.368 | -0.343* | -0.309 | -0.299 |
| | (0.241) | (0.200) | (0.246) | (0.205) | (0.258) | (0.214) |
| 2009 1 | 0.218** | 0.210* | 0.284*** | 0.261** | 0.272** | 0.247* |
| | (0.103) | (0.116) | (0.101) | (0.120) | (0.108) | (0.128) |
| 2009 2 | -0.303 | -0.261 | -0.252 | -0.206 | -0.282 | -0.249 |
| | (0.246) | (0.221) | (0.246) | (0.223) | (0.258) | (0.236) |

*Note*: These are average marginal effects (average of individual marginal effects) of IHS-transformed mature forest cover upstream on the observed (censored) dependent variable.
Standard errors in parentheses;
“***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

Table 3.6. Test on If Households Deforest Differently Within Watershed and Outside Watershed

| | **Year 1996** | **Year 2000** | **Year 2005** | **Year 2009** |
|---|---|---|---|---|
| t statistic | -0.386 | -1.536 | -2.245 | -2.878 |
| | (0.700) | (0.125) | (0.025) | (0.004) |
| Mean of percentage of forest on the lot within watershed | 29.34% | 17.74% | 14.16% | 10.02% |
| Mean of percentage of forest on the lot outside watershed | 30.26% | 20.99% | 17.63% | 13.84% |

*Notes*: Two-sample t-test (unequal variances) is performed under the null hypothesis that the difference between the mean of percentage of forest on the lot within watershed and mean of percentage of forest on the lot outside watershed is equal to zero.
p-values are in parenthesis.

Table 3.7. Durbin Wu-Hausman Test for Endogeneity of Upstream Forest on Lot

| | **IHS (cow/ pasture)** | **IHS (milk/ cow), dry** | **IHS (milk/ cow), wet** | **IHS (milk/ pasture), dry** | **IHS (milk/ pasture), wet** | **milk revenue, dry season** | **milk revenue, wet season** | **total milk revenue** |
|---|---|---|---|---|---|---|---|---|
| $\chi^2$ statistics | 2.4 | 0.98 | 1.82 | 1.04 | 2.12 | 0.77 | 1.73 | 1.73 |
| p-value | 0.121 | 0.3217 | 0.1778 | 0.3079 | 0.145 | 0.3813 | 0.1887 | 0.1878 |

*Notes*: The regressions performed are based on RE Tobit model.

Table 3.8. Marginal Effects of Upstream Forest off Lot and on Lot: No Interaction Terms

| | **IHS(cow/ pasture)** | **IHS(milk/ cow), dry** | **IHS(milk/ cow), wet** | **IHS(milk/ pasture),dry** | **IHS(milk/ pasture),wet** | **IHS(milk revenue), dry** | **IHS(milk revenue), wet** | **IHS(total milk revenue)** |
|---|---|---|---|---|---|---|---|---|
| IHS(forest off lot) | 0.097** | 0.130 | 0.153* | 0.130* | 0.151** | 0.134* | 0.147* | 0.149* |
| | (0.038) | (0.082) | (0.083) | (0.075) | (0.076) | (0.077) | (0.077) | (0.081) |
| IHS(forest on lot) | 0.002 | 0.041 | 0.045 | 0.032 | 0.038 | 0.014 | 0.018 | 0.013 |
| | (0.023) | (0.050) | (0.051) | (0.046) | (0.047) | (0.047) | (0.047) | (0.050) |
| y2000 | -0.415* | -1.348*** | -1.519*** | -1.126*** | -1.150*** | -0.408 | -0.990*** | -0.852** |
| | (0.219) | (0.465) | (0.419) | (0.416) | (0.378) | (0.369) | (0.376) | (0.399) |
| y2005 | 0.008 | -2.164*** | -1.855*** | -1.705*** | -1.389*** | -1.172*** | -1.016** | -1.004** |
| | (0.227) | (0.487) | (0.530) | (0.439) | (0.480) | (0.419) | (0.425) | (0.449) |
| y2009 | -0.710** | -1.755*** | -2.074*** | -1.635*** | -1.778*** | -0.800 | -1.483*** | -1.364** |
| | (0.293) | (0.629) | (0.582) | (0.569) | (0.528) | (0.512) | (0.516) | (0.544) |
| IHS(watershed) | -0.172** | -0.236 | -0.302* | -0.211 | -0.264 | -0.212 | -0.271* | -0.274 |
| | (0.081) | (0.174) | (0.177) | (0.160) | (0.161) | (0.163) | (0.164) | (0.172) |
| water access | 0.300* | 0.548 | 0.580 | 0.544 | 0.552 | 0.477 | 0.512 | 0.547 |
| | (0.180) | (0.389) | (0.395) | (0.360) | (0.362) | (0.369) | (0.370) | (0.387) |
| milk price | 2.185 | 2.764 | -0.398 | 4.078 | 0.741 | | | |
| | (1.385) | (2.939) | (3.396) | (2.631) | (3.068) | | | |
| lot age | 0.019 | 0.071** | 0.106*** | 0.066** | 0.097*** | 0.074*** | 0.104*** | 0.098*** |
| | (0.014) | (0.030) | (0.030) | (0.027) | (0.028) | (0.028) | (0.028) | (0.029) |
| household age | 0.020*** | 0.035*** | 0.037*** | 0.034*** | 0.036*** | 0.035*** | 0.039*** | 0.042*** |
| | (0.006) | (0.012) | (0.012) | (0.011) | (0.011) | (0.011) | (0.011) | (0.012) |
| household edu | -0.002 | -0.039 | -0.007 | -0.019 | 0.007 | -0.018 | 0.011 | 0.013 |
| | (0.032) | (0.068) | (0.069) | (0.061) | (0.063) | (0.062) | (0.063) | (0.066) |
| family | 0.044*** | 0.077** | 0.081** | 0.065** | 0.071** | 0.068** | 0.070** | 0.080*** |
| | (0.014) | (0.031) | (0.032) | (0.028) | (0.029) | (0.028) | (0.029) | (0.030) |
| soil | 0.169 | 0.231 | 0.421 | 0.234 | 0.434 | 0.306 | 0.377 | 0.400 |
| | (0.559) | (1.205) | (1.227) | (1.111) | (1.123) | (1.140) | (1.145) | (1.199) |
| IHS(slope) | 0.024 | -0.242 | -0.239 | -0.028 | -0.002 | -0.097 | -0.085 | -0.004 |
| | (0.257) | (0.557) | (0.566) | (0.514) | (0.518) | (0.527) | (0.529) | (0.554) |

Table 3.8. (continued)

| | **IHS(cow/ pasture)** | **IHS(milk/ cow), dry** | **IHS(milk/ cow), wet** | **IHS(milk/ pasture),dry** | **IHS(milk/ pasture),wet** | **IHS(milk revenue), dry** | **IHS(milk revenue), wet** | **IHS(total milk revenue)** |
|---|---|---|---|---|---|---|---|---|
| IHS(lot size) | -0.734*** | -0.776* | -1.577*** | -0.994** | -1.714*** | -0.349 | -1.017** | -0.963** |
| | (0.199) | (0.436) | (0.441) | (0.400) | (0.402) | (0.411) | (0.411) | (0.431) |
| IHS(distance) | 0.177 | -0.114 | -0.018 | 0.002 | 0.070 | -0.078 | 0.029 | -0.024 |
| | (0.153) | (0.331) | (0.336) | (0.305) | (0.308) | (0.313) | (0.314) | (0.328) |
| Municipality (spatial) fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Number of observations | 933 | 933 | 933 | 933 | 933 | 933 | 933 | 933 |

*Note*: These are average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable. The first row indicates eight specifications on the dependent variable.

In the regression of lHS(cow/pasture), “milk price” represent the average values for dry and rainy seasons. In the regression of lHS(milk/cow), dry and IHS(milk/pasture), dry, “milk price” represent values in the dry season. In the regression of lHS(milk/cow), wet and IHS(milk/pasture), wet, “milk price” represent values in the wet season.

Standard errors in parentheses.

“***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

Table 3.9. Marginal Effects of Upstream Forest off Lot and on Lot: A Full Set of Interactions

| | **IHS(cow/ pasture)** | **IHS(milk/cow), dry** | **IHS(milk/cow), wet** | **IHS(milk/ pasture), dry** | **IHS(milk/ pasture), wet** | **IHS(milk revenue), dry** | **IHS(milk revenue), wet** | **IHS(total milk revenue)** |
|---|---|---|---|---|---|---|---|---|
| IHS(forest off lot) by year and watershed group | | | | | | | | |
| 1996 1 | -0.016 | -0.254 | -0.281 | -0.132 | -0.151 | -0.128 | -0.149 | -0.162 |
| | (0.108) | (0.235) | (0.241) | (0.210) | (0.217) | (0.207) | (0.212) | (0.223) |
| 1996 2 | -0.178 | -0.443 | -0.326 | -0.395 | -0.299 | -0.409 | -0.309 | -0.351 |
| | (0.156) | (0.345) | (0.351) | (0.310) | (0.317) | (0.315) | (0.318) | (0.333) |
| 2000 1 | 0.140* | 0.207 | 0.218 | 0.180 | 0.188 | 0.194 | 0.198 | 0.219 |
| | (0.078) | (0.161) | (0.164) | (0.144) | (0.148) | (0.146) | (0.146) | (0.155) |
| 2000 2 | -0.194 | -0.335 | -0.179 | -0.306 | -0.181 | -0.352 | -0.202 | -0.275 |
| | (0.146) | (0.322) | (0.327) | (0.291) | (0.296) | (0.300) | (0.299) | (0.315) |
| 2005 1 | 0.127** | 0.222** | 0.207* | 0.228** | 0.217** | 0.218** | 0.201* | 0.214* |
| | (0.055) | (0.112) | (0.118) | (0.102) | (0.108) | (0.102) | (0.107) | (0.113) |
| 2005 2 | -0.178 | -0.421 | -0.427 | -0.396 | -0.407 | -0.441* | -0.459* | -0.411 |
| | (0.125) | (0.260) | (0.269) | (0.238) | (0.246) | (0.243) | (0.250) | (0.262) |
| 2009 1 | 0.192*** | 0.348*** | 0.392*** | 0.332*** | 0.373*** | 0.340*** | 0.369*** | 0.402*** |
| | (0.056) | (0.122) | (0.124) | (0.110) | (0.112) | (0.111) | (0.111) | (0.117) |
| 2009 2 | -0.089 | -0.424 | -0.359 | -0.348 | -0.294 | -0.382 | -0.315 | -0.348 |
| | (0.120) | (0.264) | (0.268) | (0.238) | (0.243) | (0.247) | (0.248) | (0.260) |
| IHS(forest on lot) by year and watershed group | | | | | | | | |
| 1996 1 | 0.014 | 0.051 | 0.166 | -0.027 | 0.075 | -0.055 | 0.031 | 0.024 |
| | (0.113) | (0.246) | (0.252) | (0.218) | (0.226) | (0.215) | (0.220) | (0.233) |
| 1996 2 | 0.009 | -0.104 | -0.109 | -0.074 | -0.074 | -0.175 | -0.185 | -0.192 |
| | (0.098) | (0.214) | (0.219) | (0.191) | (0.197) | (0.193) | (0.196) | (0.206) |
| 2000 1 | -0.080 | -0.197 | -0.181 | -0.175 | -0.160 | -0.192 | -0.175 | -0.205 |
| | (0.080) | (0.165) | (0.169) | (0.148) | (0.152) | (0.149) | (0.150) | (0.159) |
| 2000 2 | 0.208*** | 0.365** | 0.344** | 0.343** | 0.333** | 0.315** | 0.282** | 0.335** |
| | (0.068) | (0.154) | (0.157) | (0.139) | (0.143) | (0.142) | (0.142) | (0.150) |

Table 3.9. (continued)

| | **IHS(cow/ pasture)** | **IHS(milk/cow), dry** | **IHS(milk/cow), wet** | **IHS(milk/ pasture), dry** | **IHS(milk/ pasture), wet** | **IHS(milk revenue), dry** | **IHS(milk revenue), wet** | **IHS(total milk revenue)** |
|---|---|---|---|---|---|---|---|---|
| 2005 1 | -0.015 | -0.038 | -0.046 | -0.049 | -0.057 | -0.063 | -0.076 | -0.066 |
| | (0.047) | (0.094) | (0.101) | (0.085) | (0.092) | (0.086) | (0.091) | (0.096) |
| 2005 2 | 0.040 | 0.291*** | 0.186** | 0.283*** | 0.196** | 0.271*** | 0.185** | 0.222** |
| | (0.043) | (0.092) | (0.094) | (0.083) | (0.086) | (0.085) | (0.086) | (0.091) |
| 2009 1 | -0.091** | -0.200** | -0.130 | -0.205** | -0.145* | -0.225*** | -0.158** | -0.236*** |
| | (0.044) | (0.094) | (0.097) | (0.085) | (0.087) | (0.085) | (0.087) | (0.091) |
| 2009 2 | 0.048 | 0.141* | 0.167** | 0.132* | 0.154** | 0.125* | 0.147** | 0.154** |
| | (0.037) | (0.082) | (0.084) | (0.073) | (0.076) | (0.076) | (0.076) | (0.080) |

*Note*: These are average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable. The first row indicates eight specifications on the dependent variable.

In the regression of lHS(cow/pasture), “milk price” represent the average values for dry and rainy seasons. In the regression of lHS(milk/cow), dry and IHS(milk/pasture), dry, “milk price” represent values in the dry season. In the regression of lHS(milk/cow), wet and IHS(milk/pasture), wet, “milk price” represent values in the wet season.

Standard errors in parentheses.

“***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

Table 3.10. Marginal Effects of Forest in the 1 km Buffer

| | **IHS(cow/pasture)** | | **IHS(milk/cow), dry** | | **IHS(milk/cow), wet** | | **IHS(milk/pasture), dry** | | **IHS(milk/pasture), wet** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit | RE Tobit | Pooled Tobit |
| A. no interaction | | | | | | | | | | |
| IHS(forest 1 km buffer) | -0.0781 | -0.0480 | -0.222 | -0.157 | -0.119 | -0.0441 | -0.222 | -0.150 | -0.145 | -0.0648 |
| | (0.119) | (0.106) | (0.257) | (0.233) | (0.262) | (0.239) | (0.233) | (0.211) | (0.239) | (0.216) |
| B. year*watershed group*IHS(forest 1 km buffer) | | | | | | | | | | |
| IHS(forest 1 km buffer) by year and watershed group | | | | | | | | | | |
| 1996 1 | -0.702* | -0.582 | -1.502 | -1.110 | -1.359 | -1.080 | -1.512* | -1.120 | -1.374 | -1.094 |
| | (0.425) | (0.433) | (0.932) | (0.841) | (0.956) | (0.889) | (0.827) | (0.740) | (0.855) | (0.784) |
| 1996 2 | -0.884* | -0.655 | -1.734 | -1.271 | -1.556 | -1.165 | -1.609* | -1.144* | -1.460 | -1.078 |
| | (0.489) | (0.408) | (1.067) | (0.789) | (1.091) | (0.835) | (0.947) | (0.692) | (0.978) | (0.736) |
| 2000 1 | -0.060 | 0.004 | -0.515 | -0.294 | -0.340 | -0.131 | -0.623 | -0.415 | -0.470 | -0.275 |
| | (0.314) | (0.426) | (0.653) | (0.860) | (0.667) | (0.891) | (0.583) | (0.770) | (0.599) | (0.799) |
| 2000 2 | 0.275 | 0.334 | 0.991 | 1.138 | 1.187 | 1.323 | 0.937 | 1.078 | 1.127 | 1.258 |
| | (0.374) | (0.398) | (0.820) | (1.029) | (0.837) | (1.055) | (0.733) | (0.929) | (0.754) | (0.955) |
| 2005 1 | 0.268 | 0.303 | 0.086 | 0.182 | 0.245 | 0.350 | 0.109 | 0.206 | 0.216 | 0.318 |
| | (0.211) | (0.245) | (0.421) | (0.484) | (0.450) | (0.485) | (0.384) | (0.464) | (0.411) | (0.463) |
| 2005 2 | 0.095 | 0.101 | 0.176 | 0.133 | 0.277 | 0.268 | 0.210 | 0.169 | 0.305 | 0.299 |
| | (0.204) | (0.168) | (0.426) | (0.475) | (0.441) | (0.490) | (0.386) | (0.429) | (0.401) | (0.444) |
| 2009 1 | -0.171 | -0.156 | -0.187 | -0.097 | -0.001 | 0.061 | -0.318 | -0.200 | -0.163 | -0.079 |
| | (0.209) | (0.210) | (0.456) | (0.447) | (0.462) | (0.475) | (0.411) | (0.414) | (0.419) | (0.438) |
| 2009 2 | -0.303 | -0.249 | -0.774* | -0.685* | -0.792* | -0.662* | -0.711* | -0.607* | -0.751* | -0.616* |
| | (0.199) | (0.173) | (0.429) | (0.357) | (0.438) | (0.372) | (0.384) | (0.316) | (0.395) | (0.332) |

*Note*: These are average marginal effects (average of individual marginal effects) of IHS-transformed mature forest cover within 1 km buffer of the lot on the observed (censored) dependent variable.

Standard errors in parentheses;

“***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

Table 3.11. Lagged Effects of Upstream Forest

| | **IHS(cow/ pasture)** | **IHS(milk/ cow), dry** | **IHS(milk/ cow), wet** | **IHS(milk/ pasture),dry** | **IHS(milk/ pasture),wet** | **milk revenue, dry** | **milk revenue, wet** | **total milk revenue** |
|---|---|---|---|---|---|---|---|---|
| **A. Regression on forest off lot** | | | | | | | | |
| IHS(forest off lot) | 0.078 | 0.147 | 0.214 | 0.166 | 0.222 | 0.164 | 0.233 | 0.209 |
| | (0.084) | (0.180) | (0.186) | (0.162) | (0.168) | (0.165) | (0.168) | (0.178) |
| IHS(lagged forest off lot) | 0.024 | 0.005 | -0.045 | -0.023 | -0.061 | -0.028 | -0.092 | -0.063 |
| | (0.090) | (0.195) | (0.200) | (0.175) | (0.181) | (0.178) | (0.181) | (0.191) |
| **B. Regression on forest off lot and on lot** | | | | | | | | |
| IHS(forest off lot) | 0.066 | 0.118 | 0.166 | 0.134 | 0.171 | 0.142 | 0.188 | 0.180 |
| | (0.086) | (0.187) | (0.192) | (0.168) | (0.173) | (0.171) | (0.174) | (0.184) |
| IHS(lagged forest off lot) | 0.037 | 0.014 | -0.015 | -0.005 | -0.024 | -0.010 | -0.050 | -0.036 |
| | (0.092) | (0.199) | (0.204) | (0.179) | (0.185) | (0.183) | (0.185) | (0.196) |
| IHS(forest on lot) | 0.026 | 0.047 | 0.090 | 0.056 | 0.097 | 0.042 | 0.087 | 0.057 |
| | (0.043) | (0.092) | (0.095) | (0.083) | (0.086) | (0.084) | (0.086) | (0.090) |
| IHS(lagged forest on lot) | -0.029 | -0.008 | -0.054 | -0.029 | -0.072 | -0.034 | -0.085 | -0.055 |
| | (0.044) | (0.094) | (0.097) | (0.084) | (0.088) | (0.086) | (0.087) | (0.092) |

*Note*: These are average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable. The first row indicates eight specifications on the dependent variable.

Both regressions have no interaction terms.

Standard errors in parentheses.

“***”, “**”, “*”, indicate significance at the 1%, 5%, and 10% levels.

# CHAPTER 4: CONCLUSIONS

My dissertation analyzes the factors that drive deforestation decisions by farmers and assesses whether those farmers benefit from the remaining forests in a region typical of the agrarian reform settlements established by the Brazilian federal government throughout the Amazon. Specifically, I focus on the Von Thünen pattern of tropical deforestation and the multiple dimensions of urban access effect on land use decisions. I investigate whether and how decision-making and the drivers of deforestation change over time, which contributes to identifying the most effective approaches to reducing tropical deforestation; in particular, the conversion of forest to pasture could influence changes in ecosystem services. I then study whether the extent of forest in upstream drainages affects downstream farm production. Evidence on the existence and value of ecosystem services could encourage decision-makers to consider the benefits of standing forest and the externalities of deforestation when designing land use and other conservation policies.

In the first chapter, I put the study region in context and discuss five stylized facts about the region that may influence land use decisions and/or forest ecosystem services. In general, the Ouro Preto do Oeste region is typical of agrarian settlements as an example of global government-sponsored rural migration schemes that encourage the conversion of native vegetation land use to agriculture. In contrast to other parts of the Amazon, farm households in my study region were provided with secure land titles and allocated to relatively nutrient-rich soils. The dairy industry is the dominant agricultural activity, and milk is the main commercial product of nearly all farm families. Contrary to long-standing images of the Amazon rainforest, the study region has experienced accelerated urbanization, a distinct dry season, and severe drought years.

My study of the evolving relationship between market access and deforestation is the first to analyze the long-term evolution of deforestation at the property level in the Amazon. I incorporate multiple dimensions of urban access in a household production framework and show that their combined effect on deforestation is ambiguous and could change over time. Empirical results suggest that the year 2004 is the most significant break point. The diminishing role of transportation cost in farm-gate price, combined with increasing enforcement of environmental laws and greater labor opportunities in urban centers, forced a change in the effect of distance on deforestation from negative to positive. Specifically, in 2004, the federal government of Brazil launched a new effort to control deforestation in the Amazon as a way of mitigating climate change, and deforestation across the Amazon declined sharply from 2004 to 2012. In addition, I distinguish urban centers by the level of economic activity based on nighttime lights data. My results show that not only did total deforested area decline, but the distribution of deforestation on the landscape shifted from cities toward remote areas. This suggests that the new commitment to enforcing the forest law was effective, but also that it may have resulted in more diffuse deforestation.

In the third chapter, on forest watershed services to local populations, I find evidence that forest watershed services influence milk revenue, the stocking rate of dairy cattle, and milk productivity. Previous studies of watershed services have demonstrated that the value of forest watershed services can be measured as the change in the economic welfare of agricultural households. The framework for valuation of ecosystem services assumes that the beneficiaries are passive service users. However, in my study region, the farmers who benefit from watershed services also typically own and make land use decisions for part of that watershed. I therefore extend the standard theoretical framework to account for the endogeneity of land use decisions on the property, thus endogenizing forest watershed services. I demonstrate that even with this modification, the marginal value of watershed services is equal to the marginal profits from the services. Empirically, I find that upstream standing forest on others' farm lots provides positive economic benefits to downstream milk production when water is scarce, for farm properties fed by small drainages, and in drought years. Upstream forest on lot has both positive and negative effects on downstream milk production, depending on drainage size and water availability during the year. In general, standing forest provides insurance against drought, which raises the possibility that individual farmers could negotiate with and/or subsidize upstream neighbors by retaining forest in the parts of the drainage that lie outside their own property. This insurance function is likely to become more important in the future as rainfall in the region becomes more variable with global climate change.

There are several directions for future research. One intriguing avenue would be investigating the market access effect in the most recent years with updated land cover data. There have been two updates to the dimensions of policy enforcement and agricultural production since the study period. In the dimension of policy enforcement, the federal forest code (Federal Act 12651), which was revised in 2012, introduced new mechanisms to reduce deforestation and restore native vegetation; this has received wide attention (Brancalion et al. 2012; Soares-Filho et al.  2014). One of the most important mechanisms under the new forest code is the Environmental Reserve Quota (CRA), which allows the CRA surplus of forest on one property to offset excess deforestation on another property. Small-scale landowners (lot size less than 4 Fiscal Module)—the target individuals in our study—were granted permission to not restore native vegetation.

In the dimension of agricultural production, fish farming in the Ouro Preto do Oeste region has expanded in recent years and joins milk production as a major income source. Changes in agricultural production and policy regulations and their interaction effects would trigger adjustments in the relationship between market access and deforestation.

Furthermore, future research on forest watershed services could include the “green water” mechanism of precipitation recycling. My dissertation studies and previous literature focus on the beneficial effects of the “blue water” mechanism (stream runoff and drainage) on production, and do not explicitly model green water from forest evapotranspiration. Estimating precipitation as a function of land cover changes and its feedback for land use decisions would enrich the analysis of watershed processes and enhance investigation of the coupled natural-human system.

Another direction for future research would be to integrate the mechanism of water quality. Extensive evidence has shown that changes in forest cover influence water quality (Lowrance et al. 1984; Tong and Chen 2002; Neary et al. 2009), and both the quantity and quality of milk production are believed to be related to the quality of water intake by cattle (Challis et al. 1987; Perkins et al. 2009). Hence, explicitly testing the mechanism of water quality between upstream forest and downstream milk production would be helpful for more accurately interpreting the local benefits of watershed services.

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