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Francisco Fontes and Charles Palmer

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WAS VON THÜNEN RIGHT?

CATTLE INTENSIFICATION AND DEFORESTATION IN BRAZIL[1]

Francisco Fontes[2] and Charles Palmer[3]

Department of Geography and Environment & Grantham Research Institute on Climate Change and the Environment

London School of Economics (LSE)

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ABSTRACT

This paper examines whether patterns of cattle intensification, deforestation, and pasture expansion in the Brazilian state of Rondônia are consistent with the land rent framework, in which location and distance to markets is a key determinant of rents. A panel dataset of household lots, collected between 1996 and 2009, is used to test the hypothesis that the further a household is from market the more likely it will extensify cattle production, deforest, and expand pasture in response to rising demand for beef and milk. Results from a fixed effects model suggest empirical support for the theory. Pasture area is significantly increasing while forest is significantly decreasing in lots located further away from the market relative to those closer to the market. Patterns of land use differ, however, depending upon the forest type and commodity considered. Primary forest may be 'spared' closer to market though perhaps at the cost of greater conversion of secondary forest. Households with greater endowments of forest tend to deforest more than those with smaller ones.

Keywords: Agriculture, Cattle, Deforestation, Households, Intensification, Land Rents, Sparing

JEL classification: Q12, Q15, Q23, Q24

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[2] F.Pereira-Fontes@lse.ac.uk

[3] C.palmer1@lse.ac.uk

1. INTRODUCTION

Growth in demand for meat and dairy products, particularly in emerging market economies such as Brazil and China, has driven a huge rise in global livestock numbers. This, in turn, has had critical implications for land use change. In the Brazilian Amazon, expanding cattle populations and pasture areas as well as crop expansion are largely responsible for decades of deforestation (FAO, 2010; Nepstad et al., 2009). To counter this expansion while continuing to meet the demand for food, agricultural intensification is often promoted as a means of reducing cultivated areas, concentrating production and allowing some lands to be 'spared' (e.g. Cohn et al., 2014; Nepstad et al., 2009; Rudel et al., 2009). Between 1975 and 2006, this pattern is observed at the municipality scale in 'agriculturally consolidated' areas in the south of Brazil but not in Amazon forest frontier areas, where intensification occurred alongside agricultural expansion (Barretto et al., 2013).

In this paper, we evaluate the extent to which patterns of intensification and land use among rural households in the Amazon state of Rondônia are consistent with the land rent framework. Given rapid 'frontier urbanization' and the establishment of close to 1,000 urban centres in the Brazilian Amazon over the past 50 years (Browder and Godfrey, 1997; Brondizio, 2016),[1] this framework provides a useful basis for understanding land-use patterns at the micro-scale. Originated by von Thünen in 1826, it posits that location and distance to markets is a key determinant of rents (von Thünen, 1966). Closer to market, farmers bear lower costs in getting their products to market and since they make higher profits, rent is higher (Angelsen, 2007; Chomitz et al., 2007). Rent curves for different land uses can be mapped out as concentric circles or zones centred on a market. The frontier of each zone is located where production is no longer profitable. In a simple model with two land uses, forest and agriculture, any factor that raises agricultural rents, e.g. higher output prices, induces agricultural expansion all else equal. This pushes out the agricultural zone into the forest zone, and moves the agricultural-forest frontier, or extensive margin, further away from the market.

Rondônia experienced the most rapid land transformation of all Brazilian states between the 1980s and early 2000s (Alves, 2002). In Figure 1, patterns of forest cover (shaded dark) and agriculture in the region of Ouro Preto do Oeste appear to support the existence of an agricultural-forest frontier, one that, certainly between 1984 and 1996, has moved away from the town of Ouro Preto do Oeste. Between the town and frontier, land-use patterns follow roads and are akin to so-called 'fishbone' patterns. These are characteristic of the orthogonal settlement design, the commonest one employed by Brazil's National Institute of Colonization and Land Reform (INCRA) to resettle landless migrants in the Amazon since the 1970s.[2] Evidence for von Thünen's concentric rings appears to be weaker. Indeed, detailed satellite and survey data collected in the region suggest that many households employed multiple land uses, both intensive and extensive, regardless of location.

FIGURE 1

With a focus on cattle production, we go beyond the forest-agriculture dichotomy shown in Figure 1 to theoretically and empirically examine the extent to which patterns of land use at the household scale support a key insight of the land rent framework: factors which increase rent, e.g. price rises reflecting growing demand for agricultural commodities, will also tend to increase agricultural intensity with more intensive uses found closer to the central market (Angelsen, 2007). To better

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[1] According to Brondizio (2016), the population of the Legal Amazon in Brazil rose from 10 to 30 million between 1980 and 2010, of whom around 75% live in urban centres.

[2] Less common than the orthogonal design but also implemented by INCRA are the watershed and radial designs (Caviglia-Harris and Harris, 2011).

understand the conditions under which intensification and extensification might be adopted, we first formalise this insight in a model of an agricultural household facing the decision of whether to adopt an intensive or extensive system of cattle production. Both systems require land, labour and capital but with the latter assumed to require relatively more land and labour and fewer capital inputs than the former for a given quantity of output. In the spirit of Chomitz and Gray (1996), distance to market is included as an additional cost, which is factored directly into input and output prices. Specifically, distance to market is associated with lower net output prices, higher costs of capital inputs, and lower costs of household labour. We thus assume that the market is not only where the household's output is sold but also where capital inputs are purchased and off-farm labour opportunities are found; the further a household lives from the market, the further its members have to travel in order to work off-farm and the lower the wage received net of transport costs.

From the model, we derive the hypothesis that the further away a rural household is from the market, the more likely it will expand pasture and hence, deforest rather than intensify cattle production in response to rising demand for beef and milk. A corollary is that the closer a household is to market the more likely it will intensify production rather than expand pasture in response to rising demand. Our hypothesis is put to the test using data collected from households with privately-held lots, sampled over four waves in the Ouro Preto do Oeste region between 1996 and 2009. All of these households were resettled in the region by INCRA, mostly in the 1970s (Caviglia-Harris, 2004; Caviglia-Harris et al. 2009). Panels (b) and (c) in Figure 1 were recorded during the first and final survey waves, in 1996 and 2009, respectively. Located within the ring, drawn on Figure 1 at a radius of about 80 km from the centre of Ouro Preto do Oeste town, is our sample of household lots.

We use a fixed-effects estimator to empirically test the hypothesis. Household location, measured by distance to market, is time invariant. In a model without household fixed effects, location is likely to capture time-invariant household heterogeneity, e.g. slope and soil quality, which is not observed by the researcher but may influence the household's production decision. Thus, the effect of location could be biased. Applying fixed effects helps condition out this heterogeneity but then distance to market drops out of the model. The effect of location in a panel data framework is tested indirectly by interacting distance to market with municipality-level prices for beef and milk. Price serves as a time-varying proxy of demand for beef and milk, which is expected to influence the household's cattle production decision. This interaction allows us to examine the extent to which the household's supply response to rising demand for beef and milk is conditional on its location.

The household's response is estimated in terms of changes in self-reported cattle stocking densities, and the proportion of the lot under pasture and forest (total, primary, secondary), derived from satellite data. In addition to factors correlated with its location, the household's production decision is likely to be correlated with a number of confounding factors. To condition out these and thus focus our analysis on identifying the causal impact of distance to market and price shocks on the household's production decision, we control for: year fixed effects; municipality-specific linear time-trends; a number of time-varying household characteristics; and finally, household fixed effects.

With increasing distance to market, our results first show that lots contain higher proportions of primary but lower proportions of secondary forest. Consistent with theory, we find evidence of significant increases in pasture area in lots located further away from market relative to those closer to market, driven by rising beef prices. The reverse pattern is evidenced for milk prices. Rising milk prices are also associated with more total forest while beef prices have the opposite effect, with a significantly larger loss of total forest found in lots located further away from market. Our results for the impacts of beef and milk prices on primary forest suggest limited support for 'land sparing' in lots closer to market. There is also limited evidence for the intensification of cattle production yet this has to be set against stronger evidence for the loss of secondary forest due to rising beef prices. Milk prices, by contrast, have a positive effect on secondary forest, significantly so in lots further away from market. Further analysis first shows how the marginal rates of deforestation change depending on location and commodity and second, suggests evidence for an 'endowment effect' in which households with larger initial forest endowments deforest more than those with smaller ones.

Our paper makes a number of contributions to the literature. First, we formally integrate the household decision of whether to intensify or extensify cattle production in a von Thünen framework. Following Fernandez-Cornejo et al. (2005), who examined the adoption of herbicide-tolerant soybeans by farmers, we allow for an explicit technology decision in our static household model. Consistent with other, similar models of deforestation in the literature, e.g. van Soest et al. (2002), we treat cleared land as a variable input produced by labour, although our model, by contrast, also considers household location, different forest types and capital as a separate input.

Static models are relevant if households replace infertile plots with newly-cleared forest land each agricultural season or do not consider future production on their cleared land due to insecure tenure (Takasaki, 2007). Shifting cultivators, however, tend to farm cleared land continuously and hence, can be modelled using a dynamic optimisation approach, in which forest clearing is treated as an investment. For example, Tachibana et al. (2001) incorporate an interaction between extensive and intensive cultivation in the household's production decision. Although distance to market is not relevant in their setting, they allow for the possibility that both extensification and intensification causes deforestation, the former in primary forest, the latter in secondary growth. Interestingly, an improvement in productivity on existing agricultural land leads to a smaller shifting-cultivation area, and a lower rate of (secondary forest) deforestation at the steady state, which is suggestive of 'land sparing'. In our model, we similarly allow for the possibility of land sparing and that both extensification and intensification can cause deforestation, although this is not conditional on forest type. Instead, we differentiate between forest types according to the amount of household labour time required to clear forest, with secondary forest being less costly to clear than primary forest.

When considered as both an input and an investment, forest clearing can be modelled over two periods, e.g. Takasaki (2007), Zwane (2007). In their two-period model, Pendleton and Howe (2002) factor in the effect of transaction costs on wages, agricultural prices, and the prices of consumption goods into the household's time allocation decision. Also relevant is an explicit treatment of the trade-offs between forest clearance labour and off-farm wage, and a consideration of how differences in the productivity (and clearance costs) of primary and secondary forest influence their rates of clearance for agriculture. Higher agricultural productivity is found to increase forest clearance.[3] Since we focus on small-scale, commercial cattle production rather than shifting cultivation, we treat forest clearing as an input. This allows us to retain a static model framework. Departing from Pendleton and Howe (2002), we also incorporate a positive incentive to keep forest standing, e.g. a payment for environmental services (PES), in an extension of our model.

Empirical research on deforestation often uses distance to market as a measure of location, e.g. Pfaff (1999), Tachibana et al. (2001). Whether and how von Thünen's concentric circles get shifted over time has received less attention. Ahrends et al. (2010) map out at least three theoretically

[3] This might occur, for instance, if intensive agriculture expands due to labour-saving technological change, e.g. mechanisation, which then leads to a reduced demand for labour, thus lowering the wage rate and providing incentives for the expansion of extensive agriculture (Ruf, 2001).

consistent circles of land use over time and space, in the surrounds of Dar es Salaam, Tanzania. Although these should not be interpreted as perfect geometric patterns, they do accord with the basic predictions of the land rent framework. That said, their analysis is based largely on land use and biophysical data and the crude identification of local land uses. As such, what drove these observed land-use patterns, e.g. changes in input and output prices, cannot be empirically tested.

Using the first two waves of our dataset, Caviglia-Harris (2005) finds significantly less deforestation and smaller cattle herds with increasing distance to market but no effect on cattle stocking density. We not only extend the panel but, more crucially, account for household heterogeneity and municipality trends in our estimation framework. Caviglia-Harris and Harris (2011) investigate how settlement design affects land use and deforestation using all four waves of our dataset in a fixed-effects framework. They find that the price of milk decreases the rate of deforestation but increases the proportion of the plot deforested. Yet, they do not examine whether the effect of milk prices is conditional on location, and neglect beef prices as well as the possibility of an endowment effect. Finally, no distinction is made between primary and secondary forest. In general, empirical analyses of tropical deforestation that differentiate between primary and secondary forest are rare. Combining these, as is typical in the literature, overlooks important differences with respect to the dynamics of deforestation and the relative ecological values of different forest types (Vincent, 2016).

Our empirical analysis is the first, to our knowledge, to test whether household location and by extension von Thünen's framework, has any conditional, causal impacts on household cattle production decisions. This, in turn, enables us to examine the data for any evidence of land sparing consistent with the patterns of land uses observed by Barretto et al. (2013), albeit at the micro scale. Research on tropical deforestation using longitudinal data at the household scale remains relatively rare but is critical for improving the design of policies to capture forest externalities, such as climate and hydrological services, and biodiversity. Smallholders are only responsible for around 12% of all deforestation in the Brazilian Amazon yet against a backdrop of falling deforestation rates and expanding cattle herds, smallholder deforestation rates rose by 68% between 2005 and 2011 (Godar et al., 2014). From our results, we derive a number of implications for public policy at the household scale, with respect to resettlement, agricultural development and forest conservation.

In the remainder of the paper, we first describe the setting in Section 2, before presenting our household model in Section 3, and the dataset along with some summary statistics, in Section 4. Section 5 then outlines our empirical approach while Section 6 presents our results. We discuss these and examine their implications for public policy, in Section 7.

2. BACKGROUND

Large-scale colonization of the Amazon began in the 1960s (Bowman et al., 2012; Rudel, 2005). During this period, government policy, which partly consisted of large infrastructure investments and subsidized credit to rural households, enabled the emergence of extensive cattle ranching further fuelled by rapid increases in domestic and international demand for milk and beef. Domestic consumption of cattle products per capita increased by 13%, between 1994 and 2006 (Steiger, 2006). This trend was further reinforced by a large increase in external demand (Delgado, 2003), which contributed to an expansion of beef exports of over 400% in volume over the same period (Steiger, 2006), to the extent that Brazil became the world's largest beef exporter.

These conditions have contributed to prolonged growth in size of cattle herd, from 147 million heads of cattle in 1980 to around 200 million in 2008, with over 80% of this increase occurring in the Brazilian Amazon (McAlpine et al., 2009). In the state of Rondônia, this trend was particularly strong.

Faminow and Vosti (1997) report that Rondônia had a beef self-reliance rate (beef production relative to beef consumption) of only 6% in the 1960s. By 1991, it had the second biggest cattle herd in the region, with a self-reliance rate of 190%. Since, this trend has continued. Herd size increased from 1.7 million to 5.6 million heads of cattle, between 1990 and 2000 (Barros et al., 2002). The expansion of the cattle herd, however, came at the cost of large scale deforestation, with deforested area increasing from just 2% in 1977 to over 60% in 2005 (Caviglia-Harris et al., 2009).

Perhaps as much as 90% of the cattle herd in the Brazilian Amazon is reared for beef (McManus et al., 2016), although milk production has recently grown in importance (Dantas et al., 2016). Smallholders either specialise in beef or dairy cattle production, or instead engage in dual-purpose cattle production. The latter has become increasingly prevalent among farms smaller than 100 ha in Rondônia, and both small- and medium-sized farms have contributed to the development of beef and milk market chains (Soler et al., 2014).[4] From the farm, beef cattle are taken to slaughterhouses while milk is transported to dairy plants for storage and processing. Beef cattle, although capable of self-transport are also moved by truck, which considerably reduces smallholders' time and labour costs (Walker et al., 2002).

In estimating beef cattle-related revenues, Pacheco (2009) assumes an annual off-take of 20% of the herd, including calves, adult cows and bulls. For smallholders with few or no sales, off-take may reflect herd growth, or capital accumulation, in which the estimation of off-take represents a form of saving (Walker et al., 2002). Beef cattle production is found all over the Amazon, including frontier areas, and is perceived as being simpler, less risky, and easier to market than milk production (de Veiga et al., 2001). By contrast, Faminow (1998) finds that smallholders located near urban centres tend to specialise in dairy production. Proximity to milk markets, implying less reliance on roads for transportation in the wet season, potentially provides regular and steady income streams.

Milk production systems adopted in the Brazilian Amazon are heterogeneous, exhibiting variation in the technologies adopted by farmers and associated levels of productivity (Leite and Gomes, 2001). Yet, they tend to be small in scale and seasonal. The abundance of pasture during the rainy season provides sufficient animal feed. Conversely, milk production decreases drastically during the dry season due to the shortage of pasture (Martins et al., 2008; Santana, 2002). Milk production in Rondônia increased by around 50% between 1996 and 2006, with most production concentrated in farms ranging from 100 to 500 ha. Farms smaller than 100 ha experienced substantial intensification of land use, and the highest levels of milk production per hectare (Soler et al., 2014).

Intensive pasture-based cattle production systems in Brazil are characterized by the utilization of improved high-yielding and high-quality grass and legume cultivars, fertilization of rotationally-grazed pastures to increase forage harvest efficiency, and improved animal breeding and nutrition techniques (Latawiec et al., 2014). McManus et al. (2016) show that there has been a substantial increase in productivity in Brazilian cattle production since the 1990s, although stocking densities vary across states. In 2006, the average pasture stocking rate in Rondônia was 1.76 animal units (1 AU equivalent to 450 kg of animal live weight) per hectare, among the highest rates in the Legal Amazon and well above the average for Brazil as a whole, 0.91 AU/ha (Valentim and Andrade, 2009).

[4] In the 2006 Census, about 40% of 'utilised land' in Rondônia is used for 'family agriculture', defined as land managed by households who primarily use household labour (IBGE, 2006). Though data are patchy at municipality scale, the populations of three of our six sampled municipalities in 2006, namely Vale do Paraiso, Ouro Preto do Oeste, and Ji Paraná, were around 10,000, 40,000 and 100,000, respectively.

The potential of cattle intensification to help reduce deforestation has long received attention from researchers and policymakers alike (see, e.g. Angelsen and Kaimowitz, 2001). More recently, the capacity of intensification to raise beef and milk productivity suggests that it could potentially reduce agricultural expansion into forest, the so-called 'land sparing' effect (Phalan et al., 2011).[5] Barretto et al. (2013) demonstrate that pasture intensification at the municipality scale historically correlates with a reduction in pasture area, particularly in agriculturally consolidated areas of southern and south-eastern Brazil. While this pattern is not observed in the Amazon, Martha et al. (2012) suggest that productivity gains, made between 1996 and 2006, may have 'spared' millions of hectares of Amazon forest. However, this still leaves open the possibility that intensification in forest frontier regions may itself induce agricultural expansion, via a rebound effect (Angelsen, 1999; Lambin and Meyfroidt, 2011). Recent evidence from Vale (2015) suggests that cattle intensification need not be synonymous with more deforestation, although whether this will be sufficient to significantly slow deforestation in the Amazon remains unknown.

3. LAND RENT FRAMEWORK AND HYPOTHESES

We present a simple model of a rural household engaged in cattle production. When resettled in the 1970s onwards, such households in our setting initially converted forest to crops before purchasing cattle and converting cropland to pasture. Increasingly, households moved towards the direct conversion of forest to pasture (Caviglia-Harris et al. et al., 2014). Thus, for simplicity, we focus on using our model to better understand how, conditional on distance to market, rising beef and milk prices affect the household's allocation of labour, land and capital inputs to cattle production. A critical distinction is made between the technology adopted by the household, intensive or extensive. Formally, we develop a Chayanovian model of the agricultural household with an explicit technology decision. Here, we present only a summarized version of the model while the full details can be found in the Technical Appendix (1). We begin by assuming households have a fixed endowment of land and that markets exist for capital inputs and labour, although labour market participation is constrained by households' time endowment.[6] Our utility function is continuously differentiable, concave, additively separable, and depends on the level of consumption (*Y*) of the household, the amount of labour (off-farm (*M*) and on-farm (L_g, L_{f1}, L_{f2}) as well as the consumption of leisure (*l*):[7]

$$U(Y, L_g, L_{f1}, L_{f2}, M, l) \quad (1)$$

[5] Patterns of land sparing can be consistent with the Borlaug hypothesis, with agricultural productivity increasing forest cover.

[6] Amazon smallholders typically face a number of barriers to the intensification of their cattle production systems, including a lack of access to capital and credit as well as competition for skilled workers and technical assistance (Latawiec et al., 2014). From this, we assume that capital inputs can be purchased from the market, with their cost rising with distance to market. We also assume that labour cannot be hired in by the household. If the agricultural wage is equivalent to the off-farm wage, this will not change model outcomes, especially if there are transaction (transport) costs. Regarding participation in the labour market, decisions are made separable when households decide to have a non-zero amount of off-farm labour. Households produce up to the point where the marginal product of labour equals the wage rate. When the wage rate is too low, the household's labour decision is fully endogenous.

[7] Concavity precludes increasing marginal returns to consumption and leisure. Additively separable implies a Cobb-Douglas functional form, so that the marginal utility of leisure does not depend on the amount of consumables. Assuming some kind of interaction would mean the utility function entering every first order condition, both directly and indirectly, which unnecessarily complicates the model.

Our household's objective is to maximize its utility subject to four constraints. The first is an income constraint, in which the expenditure on consumables $(p_y Y)$ is equal to total revenues.[8] Total revenues consist of (i) farm profits, which are derived from selling Q units of the output of interest (e.g. beef or milk) at a market price net of transport costs $(p_q - td)$, net of the costs of purchasing X units of capital inputs, each purchased at a unit price of $(w_x + td)$, and (ii) off-farm earnings, where the household receives a net off-farm wage of $(w_m - td)$ for each unit of time spent in off-farm labour, *M*. We assume that transport costs, t, vary linearly with distance, d.

Following Fernandez-Cornejo et al. (2005), the second constraint is a technology constraint. Each possible technology is defined by the use of three inputs, namely variable capital inputs (e.g. high-yield grass seeds, cattle of a new breed) denoted *X*, purchased at a unit price of $(w_x + td)$, general on-farm labour, L_g, and pasture land, *P*. There are two possible technological choices, either enabling an extensive, τ_1, or intensive cattle production system, τ_2. As noted in Section 2, the intensive technology can take a number of forms and unfortunately, we do not have data for the technologies adopted in our setting. We assume that the intensive technology uses more of the capital input and uses less pasture land than the extensive technology. Thus, the levels of all of the inputs utilised depend on the technology chosen. In terms of the labour intensity of general labour (the labour intensity of the technology, net of labour required for clearing forest), the effects are ambiguous and depend on the technology adopted (Latawiec et al., 2014). As such, we assume that the increases in general labour are equivalent across the two technologies.[9]

The third constraint relates to the conversion of forest into new pasture land. Since we assume missing markets for land, the expansion of pasture is limited by the extent of a household's lot as well as the initial endowment of forest in the lot. When the entire lot area has been converted to pasture, the household can only adopt a technology if it requires no additional pasture land.[10] If forest remains in the lot, an expansion of pasture land is possible through the use of labour to clear primary (L_{f1}), secondary (L_{f2}), or both types of forest. We assume that clearing primary forest is more costly than clearing secondary forest, which is captured by the greater amount of time needed to clear a given area of primary forest.[11] Note that we also assume the household obtains no rent from keeping its forest standing, regardless of whether it is secondary or primary. Thus, the household neither harvests timber and non-timber products, nor obtains any benefits from other ecosystem services associated with forest, e.g. climate.[12] Reforestation is not possible in our model.

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[8] If the household buys consumables in the same place as they sell their output then expenditure on consumables will also be net of transport costs. We abstract from this since it does not affect the production decision (in the separable case).

[9] For understanding outward shifts of the extensive margin, Angelsen (2007) suggests that the sector, e.g. cattle production, exposed to technological progress may be more important than the nature (e.g. factor intensity) of the technology.

[10] If ∂P/∂Q=0, then the intensive technology will be adopted but if ∂P/∂Q>0, then the household cannot adopt either technology. The only option in the latter case is the status quo.

[11] This is supported, for example, by Fujisaka et al. (1996), who document that farmers in the states of Acre and Rondônia needed about 23 days/ha to clear primary forest, a number that falls to 16 days/ha to clear fallowed land. They also note that the technology required often differed, with chainsaws (which often required hiring labour) being used to clear primary forest while axes and machetes were sufficient to clear secondary forest. Pendleton and Howe (2002) also assume that secondary forest takes less time to clear than primary forest, in addition to assuming that plots derived from secondary forest are relatively less productive than those derived from primary forest.

[12] Positive externalities associated with forest can be potentially captured via a PES scheme, which we incorporate into the model in the Technical Appendix (2) and discuss further in Section 7.

We can summarize the first three constraints using the full income constraint, given by the following expression:

$$p_y Y = (p_q - td)Q[X(\tau_t), L_g(\tau_t), L_{f1}(\tau_t), L_{f2}(\tau_t), \tau_{t,}] - (w_x + td)X + (w_m - td)\, M \qquad (2)$$

Finally, we impose that the total time endowment of the household be allocated between general on-farm labour, land-clearing labour, off-farm labour and leisure:

$$T = L_g + L_{f1} + L_{f2} + M + l; M \geq 0; L_{f1} \geq 0; L_{f2} \geq 0; L_g > 0; l \geq 0 \qquad (3)$$

The Lagrangian:

$$L = U(Y, L_g, L_{f1}, L_{f2}, M, l) + \lambda[(p_q - td)Q[X(\tau_t), L_g(\tau_t), L_{f1}(\tau_t), L_{f2}(\tau_t), \tau_{t,}] - (w_x + td)X + (w_m - td)\, M - p_y Y] - \mu[T - L_g - L_{f1} - L_{f2} - M - l] \quad (4)$$

After deriving the first-order conditions (see Technical Appendix (1)), it is profitable for a household to engage in extensive cattle production, τ_1, when:

$$(p_q - td)\frac{\partial Q}{\partial \tau_1} \geq (w_x + td)\frac{\partial X}{\partial \tau_1} + \frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} + \frac{\partial L_g}{\partial \tau_1}\right) \qquad (5)$$

Thus, it is profitable to engage in extensive agriculture (τ_1>0) if the increase in revenues net of transport costs ($(p_q - td)\frac{\partial Q}{\partial \tau_1}$) exceed the costs of doing so. These costs include: (i) additional capital inputs, which comprise unit input costs net of transport costs $(w_x + td)$ multiplied by the increase in capital inputs required by the technology ($\frac{\partial X}{\partial \tau_1}$); and, (ii) the costs associated with the additional labour required by the technology. If the household works off-farm, each unit of additional labour is compared to the market wage net of transport costs. Similarly, for the adoption of an intensive system, τ_2:

$$(p_q - td)\frac{\partial Q}{\partial \tau_2} \geq (w_x + td)\frac{\partial X}{\partial \tau_2} + \frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_2} + \frac{\partial L_{f2}}{\partial \tau_2} + \frac{\partial L_g}{\partial \tau_2}\right) \qquad (6)$$

Under the assumption that a unit of intensification leads to the same increase in output as a unit of extensification $\left(\frac{\partial Q}{\partial \tau_1} = \frac{\partial Q}{\partial \tau_2}\right)$,[13] the technology adopted will depend on relative costs. If participating in a labour market, the household's value of its labour is driven by the off-farm wage, which is decreasing with distance. With increasing distance from market, off-farm wages are lower while capital inputs are more expensive. Thus, households located further away from the market are more likely to adopt the extensive rather than intensive technology, utilising a greater quantity of the cheaper input (labour) and a smaller quantity of the more expensive input (capital). Formally, the condition for the adoption of the extensive technology (assuming that the gains exceed zero for at least one of the two systems) is given by:

$$\frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} - \frac{\partial L_{f1}}{\partial \tau_2} - \frac{\partial L_{f2}}{\partial \tau_2}\right) \leq (w_x + td)\left(\frac{\partial X}{\partial \tau_2} - \frac{\partial X}{\partial \tau_1}\right) \qquad (7)$$

Since the marginal rate of substitution between leisure and consumption, $\frac{\mu}{\lambda}$, is decreasing in distance to market and $(w_x + td)$ is increasing in distance, the greater the distance to market, *d*, the more likely this condition will be satisfied, all else equal.

[13] If τ_1 and τ_2 represent indices of 'extensiveness' and 'intensiveness' (e.g. from 1 to 100), respectively, then a marginal increase in τ_2 has the same effect on output as marginal increase in τ_1. The conditions derived are those for a strictly positive level of adoption.

From the model, we hypothesise that the further away a lot is from the market a rise in beef or milk prices is, ceteris paribus, more likely to lead to lower rates of intensification and higher rates of pasture expansion and deforestation. A corollary is that the closer a lot is to market, an increase in prices of beef or milk is expected to lead to higher rates of intensification, lower rates of pasture expansion, and lower rates of deforestation. Regardless of location, primary forest is expected to be deforested at lower rates than secondary forest.

Finally, one scenario under which land sparing occurs is if the household opts for intensification over extensification. In this case, since we assume $\left(\frac{\partial P}{\partial \tau_1} > \frac{\partial P}{\partial \tau_2}\right)$, the household will spare $\left(\frac{\partial P}{\partial \tau_1} - \frac{\partial P}{\partial \tau_2}\right)$ units of forest for each extra unit of intensive technology adopted instead of extensive technology.[14] Note that adoption of a more intensive system does not necessarily imply zero deforestation but instead, that an additional unit of intensification requires less pasture than an additional unit of extensification. Less pasture in turn implies that more forest will be left standing in the lot.

4. DATASET AND SUMMARY STATISTICS

Described in detail by Caviglia-Harris et al. (2009), our dataset draws upon a sample of rural households from six municipalities in the Ouro Preto do Oeste region, in the state of Rondônia, Southwest Brazil. Rondônia has experienced large in-migration since the 1960s, with different municipalities settled at different times. All households privately own plots of land, and their land uses are tracked using both self-reported land-use data and GIS estimates of land uses, which are cross-checked for accuracy. Data also include sources of income, assets, and prices.

A key concern about the dataset is that it is highly unbalanced. The survey was conducted over four waves (1996, 2000, 2005 and 2009) and sample sizes differ substantially. Since data for beef prices were not collected in 1996, we focus our analysis on the data gathered in 2000, 2005 and 2009. In 2005, the target sample size was increased with an additional 117 lots from: (1) new settlements established since 1996; (2) a number of lots corresponding to individuals in the original sample who had moved; and (3), a small number of plots belonging to households associated with local NGOs working on sustainable agricultural practices. In Section 5, we show that our results are robust to excluding lots added to the sample in 2005. In 2009, the sample was expanded again to include over 200 additional lots. Our use of fixed effects, however, implies dropping these lots anyhow. Details of how the panel dataset is created are contained in Technical Appendix (3).

Home to about 25-30,000 people, Ouro Preto do Oeste is selected as the market from which distance to each household lot is estimated. Although we do not know the exact locations of beef and dairy processing facilities, it is the main town in the region, the second largest in Rondônia after the state capital of Ji Paraná, and a likely source of local demand. The town is also used to estimate distance to market in all previous studies that use our dataset (e.g. Sills and Caviglia-Harris, 2008). In selecting Ouro Preto do Oeste, we also checked two alternative measures of distance to market. First, the distance to Ji Paraná, which is highly correlated with distance to Ouro Preto do Oeste and thus has almost identical empirical results. Second, we checked the distance to the closest urban centre. Each municipality has at least one urban centre but since we do not have any information on the precise location of households we neither know the identity of these centres nor do we have information on the likelihood of these being a destination for agricultural output. Although most of our results hold with 'distance to nearest urban centre', the fit of the regressions is generally poorer,

[14] Thus, for $\tau_1 = \tau_2$ the household spares $((\partial P/\partial \tau_1)-(\partial P/(\partial \tau_2))*\tau_2$ units of forest. The effect is less clear when $\tau_1 < \tau_2$.

which is perhaps unsurprising given that this distance varies between 0 and 40 km. In addition to these alternative measures of distance, we considered using data for travel time to the closest urban centre in the regressions. However, over the sample period, this variable is invariant for 85% of our households. For the remaining households time differs, although the source of variation is unknown and distance by road remains constant in most cases.

From Table 1, we make a number of observations. First, average family size in our dataset is about six members per household, mostly adults. The average number of years of education of household heads is 3.24 years. Second, the average household in the sample is approximately 40 km away from Ouro Preto do Oeste, a distance that ranges from five to 82 km. Third, the three largest sources of income, in descending order, are milk, beef and perennial crops. As such, prices of milk and beef are likely to have important consequences for households' agricultural decisions. Fourth, households own relatively small lots (on average, 68 ha). In most cases, the majority of the land has already been converted into pasture. A non-negligible proportion, about 23%, remains under forest cover.

TABLE 1

The left-hand panel of Figure 2 depicts the price trends of beef and milk (the latter recorded in the wet season) over the sample period. Both show a very pronounced increase in prices. The local polynomial of real wet season milk prices (on the left y-axis), shows a consistent increase in the average price of milk over our sample period. Between 2000 to 2009, the average price of milk increased from approximately 0.22 reais (22 cents) per litre to about 0.24 reais (24 cents) per litre, which implies an increase of about 9%. The biggest increase in real milk prices in any municipality observed in our sample between 2000 and 2009 was just over five cents per litre.[15] In other municipalities, price increases during this period ranged from two to four cents per litre. Beef prices followed a similar trend, with an increase of just over 20% between 2000 and 2009. The biggest increase in beef prices in any municipality was 122 reais per steer. Increases ranged from 42 to 111 reais, with an unweighted[16] average increase of 80 reais per steer. The right-hand panel of Figure 2 shows how beef and milk prices appear to vary widely over space, with few discernible patterns.

FIGURE 2 HERE

Figures 3, 4 and 5 depict some general time trends in cattle stocking density and land-use change as well showing how these variables change with distance to market. Figure 3 shows the cattle stocking density, defined as the total number of each type of cattle (dairy, non-dairy) per ha of total lot area net of primary forest. The pattern in the left-hand panel suggests an increase in cattle stocking density over time, more so for non-dairy cattle. Non-dairy cattle have a more than three-fold higher stocking density than dairy cattle. The right-hand panel suggests that, on average, cattle stocking density declines as we move further away from the market.

FIGURE 3 HERE

Figure 4 highlights changes in the proportion of land under pasture and the number of cattle (disaggregated by type) on the lot over the sample period. The panel on the left-hand side suggests a very sharp increase in the land area under pasture and an associated increase in the number of cattle in the lot. This increase is mostly driven by expansion of the non-dairy cattle herd. Indeed, on

[15] We note, however, that real milk prices in our sample peaked in 2005 and, for the 2000-2005 period, increases in average municipality milk prices ranged from 5.8-9.2 cents per litre.

[16] Unweighted at the municipality level (i.e. we summed the increase in beef prices in the six municipalities and divided this number by six).

average, non-dairy herds are larger than dairy herds by a factor of four, although the majority of sampled households engage in dual-purpose cattle production, owning both non-dairy and dairy cattle.[17] The right-hand-side panel of Figure 4 is suggestive of a fair amount of variation in the amount of cattle and the proportion of land devoted to pasture, depending on the distance to market. Overall, the trend would seem to suggest that households living further away from market tend to allocate a smaller proportion of land to pasture and own a smaller number of cattle.

FIGURE 4

Figure 5 illustrates patterns of forest cover over time and space. First, the left-hand panel of Figure 5 is suggestive of a consistent trend of deforestation throughout our sample period, which led to the average proportion of land under total forest cover decreasing among our households. That said, the average proportion of land under secondary forest appears to be relatively stable over time, perhaps even slightly increasing. This is consistent with patterns of secondary forest succession in the Brazilian Amazon, when land used in the past for cultivating annual and perennial crops is fallowed (Caviglia-Harris et al., 2014). A second aspect, highlighted in the right-hand panel of Figure 5 is that, while the trend is non-linear, there seems to be quite a clear pattern of greater forest cover in lots located further away from the centre of Ouro Preto do Oeste.

FIGURE 5

5. METHODOLOGY AND ESTIMATION

To test the hypothesis derived in Section 3, we estimate the following fixed effects model, which corresponds to our most rigorous specification:

$$Y_{it} = \beta \boldsymbol{X_{it}} + \Omega_m t + \varphi p_{cmt} + \delta p_{cmt} * dist_i + \alpha_i + \mu_t + \varepsilon_{it} \qquad (8)$$

Equation (8) models the dependent variable *Y* for household *i* at time *t*, first as a function of our variables of interest. Thus, we estimate the coefficients on the price of commodity *c* (milk and/or beef)[18] in municipality *m* at time *t* (φp_{cmt}) and its interaction with distance to market ($\delta p_{cmt} * dist_i$). Next, we include year fixed effects μ_t, which control for common shocks affecting all households in a given year, such as weather or policy shocks, followed by a municipality-specific linear time trend ($\Omega_m t$), which accounts for common trends across households in a municipality. These help capture trends in the variables of interest that are common to the households in a particular municipality, e.g. settlement dates, [19] development of local infrastructure, local economic growth, market integration, and the development of agricultural institutions. We then add a set of time-varying household-specific controls $\boldsymbol{X}_{it}$, including household size and years of education (household heads). Finally, household fixed effects (α_i) are included in order to deal with time-invariant household-level heterogeneity, like slope and soil quality.[20]

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[17] In 2000, 81% of sampled households owned both non-dairy and dairy cattle, which rose to 84% in 2005, before dropping slightly to 82% in 2009.

[18] In our main equations, milk price is reported in reais per litre, ranging from 0.19 to 0.30 reais per litre. Beef prices range from 250 to 810 reais per steer. To make the coefficients comparable, we divide beef prices by 1,000. Thus, a 0.01 increase in the coefficient for beef is equivalent to a 10 reais increase in beef price.

[19] Different municipalities have been settled at different points in time and, as shown by Caviglia-Harris et al. (2009), municipalities tend to experience a faster rate of deforestation in the initial years of settlement.

[20] Household fixed effects should capture an unobserved effect of greater soil fertility on land more recently converted from primary forest than land converted from secondary forest.

We estimate equation (8) for cattle stocking density (dairy, non-dairy), proportion of land under pasture and proportion of land under forest cover (primary, secondary, total). Proportions are chosen over levels mainly due to the former being less sensitive to outliers than the latter. Regression results using levels remain very similar, however (see Robustness Checks in Section 6). According to the theory, we expect to observe cattle intensification in household lots closer to the market and for this effect to be less pronounced, or even reversed, in lots further away from the market, i.e. a positive sign on the coefficient φ and a potentially negative sign on the coefficient δ. We expect the proportion of land under pasture to expand in response to rising demand, an effect that is predicted to be more pronounced in lots further away from the market, i.e. a positive sign on the coefficient φ and a positive sign on the coefficient δ. That said, in the context of land sparing a negative sign on the coefficient φ is also possible. For forest cover, we expect to observe a decline in the proportion of land under forest, an effect to be more pronounced in lots further away from the market, i.e. a negative sign on the coefficient φ and a negative sign on the coefficient δ. A steeper decline in secondary forest is expected in contrast to primary forest. In the context of land sparing, a positive sign on the coefficient φ is also possible. There are, however, a number of remaining methodological issues regarding the estimation of equation (8).

First, we adopt a fixed effects framework because it allows us to control for household fixed effects, which are likely to be important in our setting to capture, for instance, (unobserved) preferences for deforestation as well as conversion costs. However, it is arguably not the best way to model proportions of land cover since it has the potential to predict values outside the possible bounds of the variable (i.e. values below 0 or above 1). To ensure that our main results are not a by-product of our methodological choice, we also present the results for a generalized linear model (GLM) model with a logistic link, as suggested by Papke and Wooldridge (1996). This estimator is able to handle proportional data which includes zeros, ones as well as intermediate values (Baum, 2008). However, the GLM estimator has the drawback of not allowing for the inclusion of fixed effects.

Second, it is highly unlikely that the error terms of different land uses are uncorrelated since conversion to one land use generally comes at the expense of another land use. Therefore, modelling the proportions separately may not be ideal. A seemingly unrelated regressions (SUR) framework could be utilized to model such land-use changes. Baum (2006) suggests that the asymptotic properties of SUR rely on having the number of time periods larger than the number of households. In our case, the number of households is much larger than the number of observations per household and hence, a SUR framework is inappropriate.

Third, household-level price data for beef and milk are arguably unlikely to be exogenous since some farmers may be, for example, better at negotiating the selling price, or simply have better connections, which allow for more favourable selling conditions. To circumvent this issue, we use the average price received by households in a certain municipality in a given year. In each year for each municipality, a relatively large number of households report the prices of beef and milk received. These are unlikely to affect the average prices received in a given municipality.[21] Reported prices within municipalities tend to be very consistent with those self-reported by our households. This also allows us to have a measure of prices for households who did not report the prices they

[21] Caviglia-Harris (2005) states that households are price takers, resulting in a small amount of price variation. However, the fact that households cannot affect prices does not mean they cannot be affected by exogenous prices which remain out of their control. It is highly likely that a number of the observed patterns in the data may be partly driven by these large and sudden increases in prices and by the sensitivity of the household response to such price changes.

received, i.e. our mean estimated prices are a good proxy of the prices faced by such households. A disadvantage of using the average of commodity prices reported at the municipality level is that it precludes the use of municipality-year fixed effects. We argue that our municipality-specific linear time trends attenuate such concerns by capturing common trends at the local scale.

All of the households in our sample resided in the same lot during the whole sample period, the size of which neither contracted nor expanded. Thus, a fourth issue is that with the inclusion of household fixed effects in our empirical specification we are unable to include the distance to the centre of Ouro Preto do Oeste, due to the fact that it is time invariant. While household fixed effects are necessary in order to capture other time-invariant factors that may drive outcomes, we opted to apply these only in our final two specifications, i.e. after the inclusion of other controls. This allows us to retain distance to market in five out of seven specifications (see Section 6). Our alternative specification (GLM with logistic link) includes distance to market in every specification.

A fifth potential issue relates to the potential endogeneity of distance to market, which implies that households may not be randomly allocated across space. Such sorting might occur, for example, when better-capitalised households choose to locate close to market. Thus, they may differ substantially from one another in a number of ways, for example, in terms of forest cover. This has been widely discussed in the literature, for example, in evaluating the impact of distance to school (Carneiro et al., 2016). However, as argued by Caviglia-Harris (2005) distance to market can be treated as exogenous in our setting since lot location and distance to market was determined by settlement plans established by INCRA.

Finally, as noted in Section 4 we have an unbalanced panel and hence, our results may be partly driven by the fact that households added in to the sample at different points in time may differ from one another. To provide assurance that our results are not driven by the inclusion or omission of the households added in 2005, we re-run the regressions using our most stringent specification as a robustness check in the following section for a sub-sample that excludes these households.

6. RESULTS

Main results

Tables 2 through to 7 summarize our main results. Since cattle stocking densities are not in proportions we only show results in Tables 2 and 3 using OLS and fixed effects estimators. The remaining tables (Tables 4-7) show the estimation results using both OLS/fixed effects and a GLM estimator with a log link. For all tables, there are seven columns which summarize our results using OLS/fixed effects: column 1 presents our OLS estimates and includes distance to market as well as beef and milk prices; column 2 incorporates an interaction term between prices and distance to market; column 3 adds year fixed effects to column 2; column 4 adds municipal time trends to column 3; column 5 adds a set of time-varying household controls to column 4; column 6 adds household fixed effects to column 5, but removes municipal trends; and, column 7 re-instates municipal trends to column 6. We remove municipal trends in column 6 in order to have more confidence in any effects picked up by our price coefficients after the inclusion of household fixed effects. In Tables 4-7, there are five additional columns containing results using the GLM estimator with a log link, which include the same variables and controls as used in OLS columns 1 to 5. We mainly focus on the OLS/fixed effects results for our most rigorous specifications, presented in OLS columns 5 to 7.

Starting with the results on cattle stocking densities (Tables 2 and 3), the coefficient of distance to market is always negative, i.e. with increasing distance and controlling for other factors cattle stocking density is lower, yet is not always statistically significant. In columns 5, 6 and 7 of both Tables 2 and 3, milk prices are associated with an increase in cattle stocking density, although this coefficient is mostly insignificant. Households that own dairy cattle also tend to own non-dairy cattle and it is possible that investments in one cattle type are influenced by price changes that affect the other type. Beef prices have an inconsistent and generally insignificant effect on stocking density.

TABLE 2

TABLE 3

We note that the significant coefficient on milk price in OLS column 7 Table 2 is quite large (23.317). It is mainly driven by the inclusion of municipal trends, which requires further explanation. First, as highlighted in Figure 3, there has been a slight increase in cattle stocking density in the sample area during the sample period. Second, changes in real milk prices tend to be relatively small (generally in the order of one to six cents per litre over the sample period). As such, the effects suggested by the coefficient are large but plausible especially given that the (omitted) municipal trends are negative yet statistically insignificant in the case of non-dairy cattle.[22] The coefficients imply that a very large change in milk prices, say five cents, increases non-dairy cattle stocking density by a range of 1.14 to 1.16 per ha, depending on the distance to market.

Regarding the proportion of land under pasture, the OLS estimates in Table 4 (column 1) suggest that pasture significantly decreases with distance to market and that it is significantly increasing with milk and beef prices. But moving from OLS column 2 to our most rigorous fixed effects specifications, in OLS columns 6 and 7, we observe a (generally) inconsistent and statistically insignificant direct effect of beef and milk prices on the proportion of land under pasture. The coefficient for distance to market remains negative but is insignificant in OLS column 5 while the coefficient of the interaction between beef prices and distance to market is always positive, which suggests an increase in the proportion of land under pasture in lots further away from the market. Indeed, the coefficient on this interaction term in OLS columns 6 and 7 implies a significant (at the 10% level) increase in the area under pasture in lots further away to the market relative to lots closer to the market. This interaction term is also consistently positive in the GLM specifications and the magnitude of the coefficient is almost identical in GLM columns 4 and 5, although it is statistically insignificant.

TABLE 4

The coefficient of the interaction between milk prices and distance to market is negative in OLS columns 6 and 7 of Table 4 though is insignificant. GLM columns 4 and 5 indicate similar results for this interaction term; indeed, they suggest a statistically significant (at the 5% level) decrease in the proportion of land under pasture in lots further away from the market. In sum, the results in Table 4 highlight differences in patterns of pasture expansion depending on the commodity.

As expected, the proportion of land under total forest cover (Table 5), which aggregates primary and secondary forest, is generally increasing with distance to market yet becomes statistically

[22] As shown in Table 2 column 6, when municipal trends are excluded the coefficient of milk prices become two to three times smaller. This is likely to be driven by two municipalities, with large, negative and significant trends. In most other cases, the inclusion of trends does not lead to large changes in the magnitude and significance of the estimated coefficients. As such, these will not be detailed for the remaining tables but are available from the authors on request.

insignificant once municipal trends are included (column 4, both GLM and OLS). Both the OLS and GLM estimates in column 1 suggest that prices are associated with significantly less total forest. In OLS columns 5, 6 and 7, total forest seems to be negatively affected by beef prices but positively affected by milk prices. In OLS column 7 this relationship is positive and significant in the case of milk. Conditional on distance to market, our results in OLS columns 6 and 7 suggest that higher prices of beef lead to a significantly larger loss in the proportion of land under total forest in lots located further away from the market in contrast to those closer to market. Similar to the OLS results, the GLM estimates also predict a negative effect of beef prices on forest cover, which becomes more pronounced in lots further away from the market. The main difference between the two sets of results is that the coefficient of the direct effect of beef price is a lot more pronounced in the GLM results, while the interaction term becomes insignificant. Both the OLS and GLM results show that higher milk prices are associated with increases in total forest cover, which could be suggestive of differences in the production of milk and beef.

TABLE 5

With respect to primary forest (Table 6), both the OLS and GLM estimates across all columns suggest that greater distance to market is significantly associated with greater proportions of land under primary forest. According to the OLS and GLM estimates in column 1, higher milk and beef prices are significantly associated with declining proportions of land in primary forest. These results are consistent with our expectations. In OLS columns 6 to 7, we observe that, conditional on the controls added, the prices of milk and beef both exhibit positive coefficients that become insignificant by column 7. Their respective interactions with distance to market are negative and significant. This implies that increases in the prices of milk and beef lead to a significant decline in land under primary forest cover in lots further away from market in contrast to those closer to market. The GLM results are consistent with the OLS results with respect to the direct effect of milk prices but not beef prices on the proportion of land under primary forest. The interaction terms tend to have a similar sign (negative), although they are insignificant in GLM columns 4 and 5.

TABLE 6

Results for secondary forest in Table 7 highlight some land-use patterns that appear to differ from those reported for primary forest in Table 6. First, the OLS estimates in column 1 suggest that greater distance to market is significantly associated with a greater proportion of secondary forest, which is consistent with our results for primary forest, as is the coefficient of milk prices (negative) but not beef prices (positive). However, moving from OLS column 2 to 7, the sign on the coefficient for distance to market switches and retains significance in most specifications. Thus, in contrast to primary forest greater distance to market is significantly associated with less secondary forest. From OLS column 2 onwards, rising prices of beef and milk both have a consistent and, where significant, negative impact on the proportion of land under secondary forest. In OLS columns 6 and 7, our results suggest beef prices significantly and negatively affect the proportion of land under secondary forest cover regardless of where the household's lot is located.

TABLE 7

From OLS column 6 in Table 7, increases in the price of milk are associated with a reduction of secondary forest, a result which while insignificant is consistent with GLM columns 4 and 5. By contrast, the results in OLS column 7 suggest that higher milk prices lead to more secondary forest. Note, however, that the result in OLS column 6 is likely to be driven by the omission of the municipality trends. The coefficient of the interaction between milk prices and distance to market in

OLS columns 6 and 7 is consistently positive, which suggests that increasing milk prices lead to a significantly higher proportion of secondary forest in lots further away from the market than those closer to the market. In general, the GLM results show patterns consistent with our OLS estimates, both in terms of sign and significance. Similar to the results for pasture, we find a different pattern depending on the commodity, with beef prices leading to larger losses in secondary forest cover and the opposite pattern holding for milk prices.

To obtain the marginal effects, specifically, the predicted mean effect of beef or milk price at varying distances to market, we insert pre-specified distances into our regressions while holding all other variables at their mean values. The full results, using the specifications in OLS column 7 for cattle stocking density (Tables 2 and 3), and OLS column 7 and GLM column 5 for our land uses (Tables 4-7), can be seen in Appendix Tables A1 and A2. From Table A1, a one cent increase in milk prices is associated with a significant increase in stocking density of non-dairy cattle, although this varies little depending on distance to market, at around 0.23 heads of cattle per hectare. The same increase in milk prices has a much smaller and statistically insignificant effect on dairy cattle. The marginal effects of beef prices on stocking density are generally insignificant.

The OLS results for pasture area in Table A1 and those for forest cover in Table A2 are transposed to Figures 6 and 7. Figure 6 shows the estimated marginal impacts of milk prices and their respective 95% confidence intervals on land use using the OLS specification in column 7 from Tables 4-7. For primary forest (panel a), a positive but insignificant marginal effect becomes negative though remains insignificant with increasing distance from the market. Consistent with our main results, the marginal effect of milk prices on secondary forest (b) becomes more positive in lots further away from market, an effect which becomes significant (at the 10% level) at distances greater than 40 km from the market. Significant positive marginal effects of milk prices on total forest (c) are found closer to market. Thus, six km away from market, a one cent increase in milk prices is associated with a 1.49 percentage point increase in total forest, which gradually declines with increasing distance from market (see Table A2). Although insignificant, the marginal effects of milk price on pasture are positive and declining with greater distance to market.

FIGURE 6

FIGURE 7

From Table 5, increases in the price of beef lead to a significantly greater decline in the proportion of total forest in lots located further away from the market. The estimated marginal effects can be seen in Figure 7 (c), which combines the marginal effects of beef prices on primary (a) and secondary (b) forest. Much of the forest loss is secondary forest, with the marginal effect on total forest becoming more negative in lots located further from market: a 10 reais increase in the price of beef leads to an estimated reduction of 0.71 percentage points in total forest cover in lots located six km from the market, and a reduction of 2.17 percentage points in lots located 80 km from the market. Consistent with our main results, Figure 7 (d) shows a negative though insignificant effect of beef prices on pasture and a less pronounced effect the further away the lot is from market. After a certain distance, about 40 km from market, the predicted effect is positive, although it remains insignificant.

The marginal effects of beef and milk prices on primary forest are insignificant throughout. Yet, both have a positive effect in lots located closer to market, at least until about 55 km distant (see Figures 6(a) and 7(a); Tables A1 and A2). One explanation for the possible 'sparing' of primary forest closer to market is the Forest Code's emphasis on the 'maintenance' of forest under Legal Reserve requirements. Land left to regenerate into secondary forest may not have the same protective status as primary forest. Smallholders in the Legal Amazon are required to maintain 80% of their land under forest under the Code.[23] While we might expect this requirement to be more binding closer to market due to the potential for better monitoring and hence, greater compliance, fewer than 1% of households appeared to comply with the Code over the sample period.

The effects of beef and milk prices on secondary forest clearly differ. Extensification and cattle reared for beef mostly explains the expansion of pasture area and decline of secondary forest, which becomes more pronounced with increasing distance from market (Figure 7(b) and (d)). The more pronounced loss of secondary vis-à-vis primary forest may in part be due to the former's lower conversion costs, in terms of household labour time (see Fujisaka et al., 1996). By contrast, milk prices have a positive marginal effect on secondary forest at each and every distance (Figure 6(b)). Combined, the marginal effects of milk prices on primary and secondary forest underlie positive and mostly significant marginal effects on total forest. This provides stronger evidence of a `sparing' effect, the size of which is contingent on household location. But since the majority of our households are dual-purpose cattle producers, this effect would need to be evaluated in light of the strong negative impact of beef prices on secondary forest cover. Note also, that these positive marginal effects should be considered in the general context of background deforestation trends.

Different production systems for beef and milk may help explain our results. Dairy systems are likely to be smaller in scale and more intensive than those systems that mainly or only focus on beef production (see Cohn et al., 2011). Although this does not seem to be reflected in our cattle stocking density data shown in Figure 3, we note from Figure 4 that dairy herds tend to be substantially smaller than non-dairy herds yet milk sales, on average, generate more household income than beef sales (see Table 1). Finally, since more secondary and less primary forest is found closer to market an 'endowment effect' might help explain the role of location in observed patterns of forest change, and how these differ depending on commodity. We examine households' initial endowment of forest after testing for the robustness of our main results in the following sub-section.

Robustness checks

We undertake a number of checks, which are shown in Tables A3 (cattle stocking density and pasture) and A4 (forest) in the Appendix. For each dependent variable we perform four robustness checks using our most stringent specification (OLS column 7 in Tables 2-7): the `No 2005' column excludes households added in 2005; the `levels' and `logs' columns use the levels and the natural logarithm of the levels as the dependent variable, respectively; and, the `l.prices' column uses lagged values of prices rather than the contemporaneous values as households may need time to react to changes in prices. With regards to cattle stocking density (Table A3), our main result of note, the direct effect of milk price on non-dairy stocking density in Table 2, is always positive and is significant in one robustness check ('No 2005'). For pasture, the coefficient of the interaction between beef price and distance to market is positive and significant in all four checks, and the interaction between milk prices and distance is significant in none. The direct effects of milk and beef prices are, respectively, always positive and negative, and both are significant in three out of four checks ('No 2005', 'Levels', 'Logs'). These results for the proportion of lot under pasture are all consistent with our main results (see Table 4); indeed they display higher levels of significance.

[23] The original Forest Code of 1965 required that smallholders in the Legal Amazon maintain forest on 50% of their land ('Legal Reserve'). This was raised to 80% by presidential decree in 1996 and implemented in 2001 (Soares-Filho et al., 2014).

For total forest, the coefficient on milk price is positive for three out of four checks but is not significant (Table A4). The coefficient on beef prices is even more inconsistent while the interaction term between distance to market and beef price is negative in all four checks and significant in two ('No 2005' and 'Levels'), which is consistent with our main results (see Table 5). For primary forest, the sign of the coefficient of milk price is consistent with our main results (Table 6) in all four checks, and significant in one ('Logs'). Regarding beef prices, the signs remain the same in three checks and significant in two ('No 2005' and 'Logs'). The interaction terms have similar, negative signs as in our main results and are significant for the milk price-distance term in three out of four checks ('No 2005', 'Logs' and 'l. prices'), and significant in one check ('Logs') for the beef price-distance term. Our secondary forest checks are also consistent with our main results in Table 7. First, the price of beef has a direct effect with a similar sign and significance in two checks ('No 2005' and 'Levels'). Interestingly, the direct effect of milk price is negative and signficant in two checks ('Logs' and 'Lagged Prices'). The coefficient of the milk price-distance interaction term is consistent with our main results: positive in all checks and significant in two ('No 2005' and 'Logs'). Also noteworthy and consistent with our main results is the coefficient of the beef price-distance interaction term, which is negative in all four checks, and significant in three ('No 2005', 'Levels', 'Logs').

Further results: endowment effects

We investigate the extent to which the initial proportion of forest, i.e. in the first period of data collection, plays a role in understanding our main results. High initial forest cover is expected to affect the household production decision: with abundant forest remaining, households may be more likely to extensify rather than intensify, regardless of location. We therefore split the sample into above- (`high') and below-median (`low') initial total forest, with the median estimated as 21.6%.[24] Based on this sample split, we test for differences in outcomes. Tables 8 and 9 show the results. For each dependent variable we use the most rigorous specification from Tables 2-7, in OLS column 7.

TABLE 8

TABLE 9

In Table 8, the significant effect of milk price on non-dairy cattle stocking density is concentrated in lots with a high endowment of total forest, which is somewhat counter-intuitive. More intuitive is the significant and positive effect of beef prices on pasture in lots further away from market, which is also largely confined to lots with a high endowment of total forest. In Table 9, a significant and positive effect of milk prices on total forest is found among households with a low forest endowment, and a significant and negative effect of beef prices among those with a high endowment. The latter effect is particularly pronounced in high-endowment households located further away from market. A positive and significant effect of beef prices on primary forest is found among households with a low forest endowment, although this effect is significantly less pronounced in lots located further away from market. The significant, negative impact of beef prices on secondary forest occurs not only irrespective of location but also regardless of forest

[24] Initial total forest cover is total forest cover in 2000 or in the first year for which we have data on the household. Initially, we investigated the possibility of splitting the sample according to the threshold of 80% of land under forest as required under the Forest Code. Given that so few households in our sample maintained this level of forest cover, we then looked to the requirements applied to other Brazilian smallholders as a rationale for dividing up our sample. Those living in grasslands within the Legal Amazon and elsewhere (i.e. outside the Legal Amazon) are required to maintain 20% of their land under forest. Our chosen threshold of 21.6% does not differ much from the 20% threshold.

endowment. Similarly regardless of forest endowment, households located further away from market spare more secondary forest in response to increases in milk prices than those close to market.

Finally, we estimate the marginal effects in our sub-samples of households split according to total forest endowment. These results are shown in Tables A5 (cattle stocking density and pasture) and A6 (forest) in the Appendix. The positive, marginal effect of milk prices on non-dairy stocking density is only significant (at the 10% level) for households with a high forest endowment close to the market. We also find a negative but insignificant effect of milk prices on the proportion of land under pasture among low-endowment households at all distances to market. Among high-endowment households, an insignificant positive marginal effect of milk and beef prices on pasture is found for households at almost all distances (Table A5).

Milk prices have positive estimated marginal effects on total forest among all households (Table A6). For households with high endowments, there seems to be lower marginal increases in total forest cover when located closer to, rather than further away from, market. Specifically, a one-cent increase in milk prices is associated with a 1.8 percentage point albeit insignificant increase in total forest eight km from the market, which rises to a significant 3.2 percentage point increase 82 km from the market. This pattern is mainly driven by secondary forest. The reverse pattern holds for low-endowment households: a one-cent increase in milk prices is associated with a significant 1.2 percentage point increase in total forest six km from the market, which falls to a 0.7 percentage point increase 77 km from the market. This pattern combines positive marginal effects on secondary forest, which rise with distance to market, with positive marginal effects on primary forest that decline, indeed becoming negative, with distance to market.

Beef prices have negative and significant marginal effects on the forest cover of both low- and high-endowment households. A 10 reais increase in beef prices is associated with a statistically significant decline of 1.4 percentage points in the proportion of land under secondary forest among high-endowment households seven km away from the market (Table A6). By contrast, the marginal decline among low-endowment households is 0.5 percentage points at around the same distance to market, a third of the size of the marginal effect estimated for high-endowment households. At 80 km distant from the market, the marginal effect on secondary forest becomes more negative with a 10 reais increase in beef prices associated with a 2.8 and 0.8 percentage point decrease in secondary forest among high- and low-endowment households, respectively. For primary forest, the marginal effects are generally positive but are only significant for low-endowment households located closer to market. Interestingly, the point estimates of this effect are substantially larger for low-endowment households than for high-endowment households. Negative marginal effects dominate total forest, although at all distances to market they are substantially larger among high-endowment households than among low-endowment ones, which is intuitive.

7. DISCUSSION AND POLICY IMPLICATIONS

Brazil has a long history of tropical deforestation, although recent trends suggest that the rate of deforestation has slowed down. Nepstad et al. (2014) argue that for Brazil to maintain progress in reducing deforestation in the Amazon, one of the steps it must take is the stabilization and intensification of cattle ranching. Against expectations, Vale (2015) argues that this trend has already started in the Amazon and, at the municipality scale he finds that the increase in productivity of cattle is associated with less deforestation. However, there is a dearth of research exploring the intensification-deforestation nexus at the household level, which is at least partly due to the paucity of available data at this level of aggregation. As such, our paper contributes to improving our understanding of how different economic, lot and household characteristics drive changes in land use. Our results suggest that market prices of beef and milk have relatively more consistent and significant effects in terms of driving land-use change in Rondônia than on cattle stocking densities.

Consistent with the land rent framework, we find evidence that rising prices were responsible for significant increases in pasture area and significantly more deforestation in lots located further away from market relative to those closer to market. Land-use patterns differ markedly depending on whether we consider primary or secondary forest, milk or beef prices, and initial household forest endowments. In lots further from market, primary forest is more abundant than secondary forest. Given the relative abundance of the latter in lots located closer to market, it is perhaps unsurprising that in these lots we observe weaker impacts on primary forest while finding stronger impacts on secondary forest. This could help explain why the coefficients of both beef and milk prices are positive in lots closer to market with respect to their effects on primary forest, which is suggestive of land sparing. Any possible 'sparing' of remaining forest should, however, be viewed in light of secondary forest loss driven by rising beef prices. These results, to some extent, may also capture endowment effects. Although milk production requires less land than beef production, our cattle stocking density results suggest that household location does not play a strong role in patterns of intensification. That said, the estimated coefficients of cattle stocking density are noisy and, for the most part, insignificant. Also, the fit of our regressions is better when analysing land-use changes in contrast to cattle stocking densities.

Our results offer a number of implications for public policy, specifically policy related to resettlement, agricultural development, and forest protection in smallholder lots. Given the importance of the Brazilian Amazon for biodiversity conservation and efforts to reduce carbon dioxide emissions from deforestation and degradation (REDD+), we examine the policy implications of our results in all three policy areas in terms of land-use change.

Further away from market we find land uses dominated by deforestation and extensification, particularly with respect to beef prices. Resettlement policies could be designed to mitigate against these land-use trends. Although land closer to urban agglomerations tends to be more expensive than land further away (Sills and Caviglia-Harris, 2008), a first policy implication is simply to allocate land to households closer to market rather than at the forest-agricultural frontier, as has been the policy in the past. Given the rise of hundreds of new small towns in parts of the Brazilian Amazon that once formed part of the forest-agricultural frontier, there is a surfeit of agricultural-forest mosaiclands. While such lands would command a higher price in contrast to frontier areas, assigning households to these rather than to lots at the frontier might help prevent the 'legal deforestation' that is likely to occur in the latter, more forest-rich lots. Our estimated marginal effects could enable the identification of possible zones in which deforestation and extensification are least likely to occur and hence, where new settlements could potentially be located.

Second, our results suggest an endowment effect whereby households in lots with relatively large remaining areas of forest tend to be far more responsive to price changes than households with less forest. Conceptually, this is perhaps an obvious point but it does imply that policy-makers aiming to intensify cattle production should focus on households still owning proportionally larger areas of forest rather than those with relatively little forest remaining on their lots. Relatedly, policy-makers keen to incentivise and nudge households into more sustainable patterns of cattle ranching in the Amazon could also focus on cattle reared for milk production, which appear to have greater potential for land sparing effects than cattle reared for beef. Thus, agricultural policies could channel extension activities, credit, and technical support towards the development of dairy herds and associated infrastructure and institutions, rather than towards non-dairy herds.

Third, the endowment effect suggests that policy-makers should move away from forest conservation policies that focus on reducing deforestation in areas with relatively little total forest. That said, our results suggest that policies geared towards protecting primary forest should target households with smaller total forest endowments located further away from market. This is perhaps pertinent given that that lots located close to market may even be sparing forest, with or without the intensification of cattle production. Thus, deforestation baselines established at a more aggregate scale, e.g. for REDD+ initiatives at the state level, are likely to be overestimating rates of deforestation in areas close to urban centres. Our results, particularly the estimated marginal effects, could be used to design more precise deforestation baselines, i.e. not only according to distance to market but also according to forest type, in order to help evaluate the impact of such initiatives as they are rolled out.

Preventing legal deforestation on smallholder lots could be achieved by positive incentives created through a market for Environmental Reserve Quotas (*cotas de reserve ambiental*; CRA), which is presently being considered by federal and state governments (Soares-Filho et al., 2014). Thus, in the revised Forest Code, approved in 2012, lots that had reduced their legal reserve below the stipulated levels before 2008 are allowed to come into compliance either by restoring their forests to cover their legal reserve deficit or by compensating for their deficit by purchasing CRA from lots with a legal reserve surplus (Cai et al., 2016). Since none of our sampled households have a legal reserve surplus, they might potentially have to purchase CRA from those that do have a surplus. Such purchases could be made via a PES scheme. Also, PES could be a means by which social values of forests, like those related to biodiversity and carbon sequestration, could be internalised. We extend our model to incorporate a PES, which can be seen in the Technical Appendix (2). The result is intuitive in that it leads to fewer incentives to adopt an intensive or extensive technology if either involves the conversion of forest into pasture. That said, a PES is theoretically more likely to incentivise the adoption of an intensive technology vis-à-vis an extensive technology, and the higher the level of the payment the more effective this incentive is likely to be. Further development of the theory, e.g. targeting primary rather than secondary forest, is left for future work.

Finally, our empirical results could be used not only to establish baselines for forest trends and as a means of monitoring compliance with the revised Forest Code over time and space, but also as a way of identifying households that pose the greatest (legal) deforestation risk, e.g. those living further away from market with predominantly non-dairy cattle herds. Such households could be targeted for PES and/or intensification strategies. One issue that would need to be examined more closely is the need to differentiate between primary and secondary forest, in terms of their relative ecological values and associated externalities, which could help with the setting of the level of the positive incentive. Further theoretical and empirical work could closely examine the relationship between incentives for forest conservation and intensification, for example, through a randomised controlled trial.

8. REFERENCES

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9. FIGURES AND TABLES

Figure 1: Forest cover around Ouro Preto do Oeste (Google Earth)

(a) 1984

(b) 1996

(c) 2009

(d) 2014

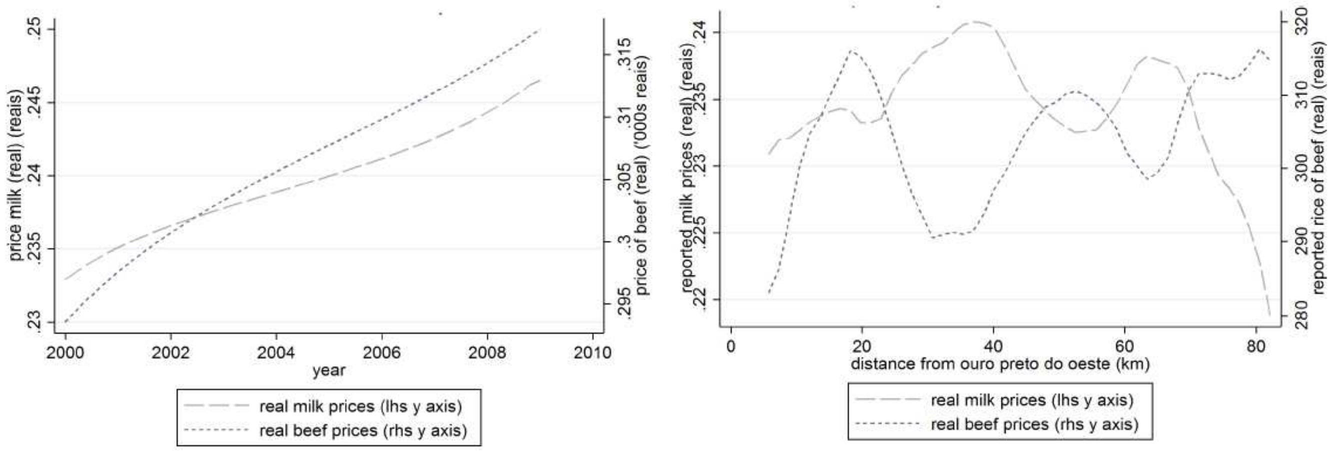
Source: Google Earth Engine Team (2015)

Table 1: Summary Statistics of observations in the sample

Variables	N	Mean	S.D	Min	Max
Household composition (number of):					
Household members	745	5.75	4.15	0.00	36.00
Adult males (age above 10)	745	2.49	1.78	0.00	10.00
Adult females (age above 10)	745	2.20	1.66	0.00	12.00
Male children (age below 10)	745	0.57	1.01	0.00	11.00
Female children (age below 10)	745	0.49	0.93	0.00	10.00
Other household characterisitics					
Age of household heads (average), years	743	48.03	13.82	18.00	81.00
Education of household heads (average), years	742	3.24	2.30	0.00	13.00
Income sources: income (2000 reais)					
Off-farm labor	625	2213.44	4770.53	0.00	50000.00
Perennial crops	743	2829.62	26360.04	0.00	665082.90
Annual crops	743	277.17	1470.72	0.00	19808.15
Beef sales	725	3419.13	12359.92	0.00	193370.20
Milk	526	6101.88	6637.19	0.00	58828.59
Social security (pensions)	746	1643.91	2306.18	0.00	12418.90
Bolsa familia program (family grants)	582	69.64	222.84	0.00	1540.49
Bolsa escola program (school grants)	582	7.40	56.66	0.00	713.09
Honey and fish	742	68.34	427.15	0.00	7348.07
Other livestock	746	1018.22	2253.38	0.00	20635.36
Land uses					
Lot size (GIS, ha)	746	68.34	34.48	5.69	148.77
Agriculture area (ha) (reported)	743	4.19	6.41	0.00	76.19
Proportion of lot under agriculture (reported)	721	0.11	0.16	0.00	1.67
Pasture area (ha) (GIS)	746	49.86	29.20	2.00	109.03
Proportion of lot under pasture (GIS)	746	0.74	0.21	0.04	1.00
Primary forest (ha) (GIS)	746	10.80	13.21	0.00	91.85
Primary forest as a proportion of lot size (GIS)	746	0.15	0.15	0.00	0.92
Secondary forest (ha) (GIS)	746	4.94	6.44	0.00	43.54
Secondary forest as a proportion of lot size (GIS)	746	0.08	0.10	0.00	0.64
Total forest cover (ha) (GIS)	746	15.74	16.32	0.00	93.46
Total forest cover as a proportion of lot size (GIS)	746	0.23	0.19	0.00	0.94
Cattle stocking density					
Non-dairy cattle per ha (net of forest)	735	1.34	1.37	0.00	15.98
Dairy cattle per ha (net of forest)	738	0.38	0.42	0.00	3.87
Market variables					
Beef price (real prices, '000 reais)	745	0.31	0.05	0.25	0.42
Milk price (real prices, reais)	745	0.24	0.03	0.18	0.28
Distance to the centre of Ouro Preto do Oeste (km)	746	40.18	18.48	5.26	82.13
Distance to Ji-Paraná (km)	746	83.47	24.87	16.25	135.14
Distance to closest urban centre (km)	746	15.59	7.28	1.19	38.24

Notes: Beef prices denote the average municipal beef price reported in the municipio. Milk price refers to the average milk price reported in the municipio for the wet season. All data are self-reported unless otherwise indicated.

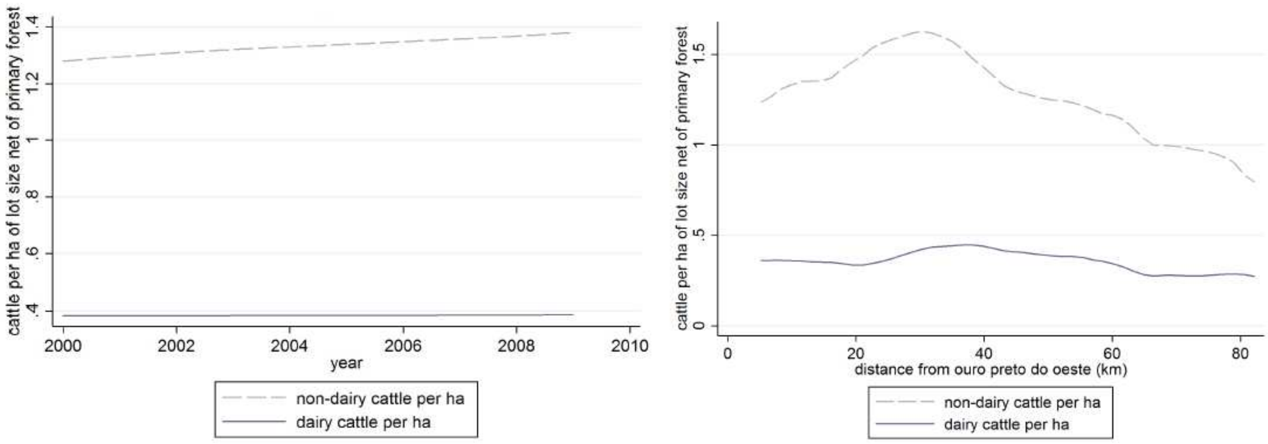
Figure 2: Milk and beef prices



(a) average municipal prices over time, 2000-2010

(b) reported prices by distance from Ouro Preto do Oeste, km

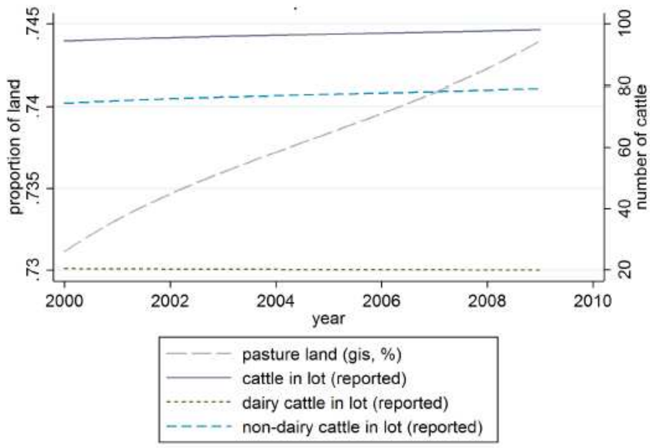
Figure 3: Cattle stocking density



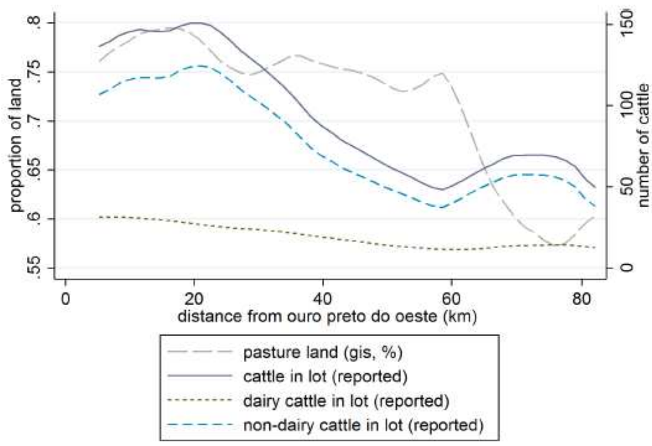
(a) over time, 2000-2010

(b) by distance from Ouro Preto do Oeste, km

Figure 4: Proportion of land under pasture and number of cattle in the lot

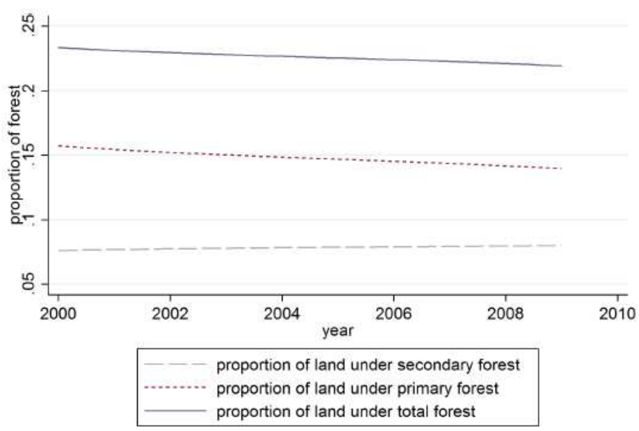


(a) over time, 2000-2010

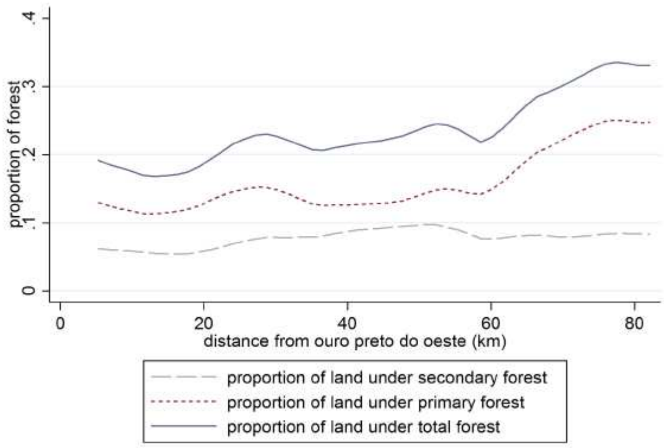


(b) by distance from Ouro Preto do Oeste, km

Figure 5: Proportion of land under forest cover



(a) over time, 2000-2010



(b) by distance from Ouro Preto do Oeste, km

Table 2: Non-dairy cattle stocking density regression results - OLS

	OLS						
Variables	1	2	3	4	5	6	7
Distance to Ouro Preto do Oeste (OPO) (km)	-0.008**	-0.03	-0.038**	-0.044*	-0.047*		
	(0.003)	(0.018)	(0.019)	(0.025)	(0.025)		
Av. milk price in the municipio (real)	2.336*	0.049	7.016	7.267	5.892	10.049	23.317*
	(1.349)	(3.015)	(6.062)	(7.540)	(7.893)	(6.571)	(11.860)
Av. beef price in the municipio (real)	3.800***	2.835	1.83	-1.966	-2.502	-0.832	2.161
	(1.215)	(2.675)	(3.904)	(4.451)	(4.361)	(3.494)	(6.456)
Av. milk price in the municipio (real) * distance OPO		0.061	0.081	0.107	0.113	0.046	-0.006
		(0.069)	(0.074)	(0.076)	(0.079)	(0.091)	(0.110)
Av. Beef price in the municipio (real) * distance OPO		0.026	0.039	0.032	0.033	-0.025	-0.121
		(0.067)	(0.065)	(0.073)	(0.073)	(0.056)	(0.077)
Year fixed effects			✓	✓	✓	✓	✓
Municipality trends				✓	✓		✓
Controls					✓	✓	✓
Household fixed effects						✓	✓
Number of observations	734	734	734	734	730	730	730
Number of households	352	352	352	352	351	351	351
R-squared	0.026	0.024	0.024	0.036	0.039	0.022	0.037

Notes: Values in parentheses denote standard errors at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.
For all specifications with no fixed effects controls include the average age of the heads of household, the average years of education of the heads of the household, lot size (ha, GIS estimate) and household size. For specifications with fixed effects, lot size is omitted as it is time-invariant.

Table 3: Dairy cattle stocking density regression results - OLS

	OLS						
Variables	1	2	3	4	5	6	7
Distance to Ouro Preto do Oeste (OPO) (km)	-0.001	-0.011*	-0.015**	-0.002	-0.007		
	(0.001)	(0.006)	(0.006)	(0.008)	(0.008)		
Av. milk price in the municipio (real)	2.632***	1.463	5.485**	2.915	2.672	1.83	1.718
	(0.441)	(0.967)	(2.436)	(2.282)	(2.332)	(2.257)	(2.992)
Av. beef price in the municipio (real)	-0.784***	-1.060**	-2.069***	0.894	-0.082	-0.292	0.182
	(0.226)	(0.458)	(0.784)	(1.215)	(1.294)	(0.881)	(1.707)
Av. milk price in the municipio (real) * distance OPO		0.031	0.046**	0.007	0.02	0.011	-0.002
		(0.023)	(0.023)	(0.028)	(0.028)	(0.024)	(0.031)
Av. Beef price in the municipio (real) * distance OPO		0.008	0.013	-0.008	-0.002	0.005	-0.011
		(0.011)	(0.012)	(0.015)	(0.015)	(0.013)	(0.023)
Year fixed effects			✓	✓	✓	✓	✓
Municipality trends				✓	✓		✓
Controls					✓	✓	✓
Household fixed effects						✓	✓
Number of observations	737	737	737	737	732	732	732
Number of households	352	352	352	352	351	351	351
R-squared	0.042	0.04	0.047	0.059	0.077	0.079	0.076

Notes: Values in parentheses denote clustered standard errors at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.
For all specifications with no fixed effects controls include the average age of the heads of household, the average years of education of the heads of the household, lot size (ha, GIS estimate) and household size. For specifications with fixed effects, lot size is omitted as it is time-invariant.

Table 4: Pasture regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Distance to Ouro Preto do Oeste (OPO) (km)	-0.013***	-0.025	-0.031*	0.011	0.008	-0.002***	-0.007*	-0.008*	0	-0.001		
	(0.003)	(0.017)	(0.019)	(0.021)	(0.022)	(0.001)	(0.004)	(0.004)	(0.004)	(0.005)		
Av. milk price in the municipio (real)	4.715***	5.686**	9.478*	-2.573	-1.401	0.926***	0.855**	1.686*	-0.945	-0.686	-0.065	0.906
	(0.977)	(2.263)	(4.862)	(5.129)	(5.320)	(0.193)	(0.418)	(0.977)	(1.061)	(1.101)	(0.879)	(1.003)
Av. beef price in the municipio (real)	0.985*	-1.284	-3.146	4.619*	3.431	0.199*	-0.258	-0.635*	0.964*	0.7	-0.265	-0.791
	(0.575)	(1.224)	(1.960)	(2.599)	(2.755)	(0.109)	(0.230)	(0.369)	(0.505)	(0.541)	(0.329)	(0.530)
Av. milk price in the municipio (real) * distance OPO		-0.024	0.004	-0.140**	-0.136**		0.002	0.006	-0.02	-0.019	-0.013	-0.002
		(0.055)	(0.058)	(0.064)	(0.066)		(0.011)	(0.011)	(0.012)	(0.013)	(0.010)	(0.011)
Av. Beef price in the municipio (real) * distance OPO		0.058*	0.060*	0.013	0.018		0.012*	0.013*	0.005	0.006	0.014**	0.019**
		(0.032)	(0.034)	(0.043)	(0.043)		(0.007)	(0.007)	(0.009)	(0.009)	(0.006)	(0.008)
Year fixed effects			✓	✓	✓			✓	✓	✓	✓	✓
Municipality trends				✓	✓				✓	✓		✓
Controls					✓					✓	✓	✓
Household fixed effects											✓	✓
Number of observations	745	745	745	745	740	745	745	745	745	740	740	740
Number of households	353	353	353	353	352	353	353	353	353	352	352	352
R-squared						0.063	0.063	0.064	0.117	0.133	0.112	0.119

Notes: Values in parentheses denote clustered standard errors at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. For all specifications with no fixed effects controls include the average age of the heads of household, the average years of education of the heads of the household, lot size (ha, GIS estimate) and household size. For specifications with fixed effects, lot size is omitted as it is time-invariant.

Table 5: Total forest regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Distance to Ouro Preto do Oeste (OPO) (km)	0.010***	0.048***	0.050**	0.001	-0.001	0.002***	0.011***	0.011***	0.003	0.003		
	(0.003)	(0.018)	(0.020)	(0.022)	(0.023)	(0.001)	(0.004)	(0.004)	(0.004)	(0.004)		
Av. milk price in the municipio (real)	-4.457***	-1.571	-3.141	6.832	5.069	-0.811***	-0.084	-0.322	1.785*	1.447	0.85	1.496**
	(1.055)	(2.317)	(4.631)	(5.210)	(5.350)	(0.196)	(0.405)	(0.849)	(1.012)	(1.036)	(0.655)	(0.708)
Av. beef price in the municipio (real)	-2.056***	0.57	0.685	-9.536***	-9.116***	-0.362***	0.176	0.195	-1.707***	-1.621***	-0.215	-0.588
	(0.587)	(1.273)	(2.013)	(2.778)	(2.842)	(0.100)	(0.212)	(0.335)	(0.476)	(0.494)	(0.270)	(0.445)
Av. milk price in the municipio (real) * distance OPO		-0.073	-0.078	0.08	0.085		-0.019*	-0.020*	0.006	0.007	-0.005	-0.001
		(0.055)	(0.062)	(0.067)	(0.070)		(0.011)	(0.011)	(0.012)	(0.013)	(0.008)	(0.010)
Av. Beef price in the municipio (real) * distance OPO		-0.067**	-0.071**	-0.004	-0.005		-0.015**	-0.015**	-0.005	-0.005	-0.017***	-0.020***
		(0.032)	(0.034)	(0.043)	(0.044)		(0.006)	(0.006)	(0.008)	(0.008)	(0.005)	(0.007)
Year fixed effects			✓	✓	✓			✓	✓	✓	✓	✓
Municipality trends				✓	✓				✓	✓		✓
Controls					✓					✓	✓	✓
Household fixed effects											✓	✓
Number of observations	745	745	745	745	740	745	745	745	745	740	740	740
Number of households	353	353	353	353	352	353	353	353	353	352	352	352
R-squared						0.049	0.053	0.051	0.103	0.119	0.202	0.21

Notes: Values in parentheses denote clustered standard errors at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. For all specifications with no fixed effects controls include the average age of the heads of household, the average years of education of the heads of the household, lot size (ha, GIS estimate) and household size. For specifications with fixed effects, lot size is omitted as it is time-invariant.

Table 6: Primary forest regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Distance to Ouro Preto do Oeste (OPO) (km)	0.011***	0.077***	0.080***	0.032	0.038*	0.001***	0.014***	0.014***	0.007**	0.008***		
	(0.003)	(0.018)	(0.021)	(0.022)	(0.022)	(0.000)	(0.003)	(0.003)	(0.003)	(0.003)		
Av. milk price in the municipio (real)	-3.182***	3.493	3.664	13.063**	12.423**	-0.446***	0.647**	0.79	2.275***	2.184**	1.044*	0.901
	(1.130)	(2.527)	(5.016)	(5.499)	(5.701)	(0.160)	(0.320)	(0.690)	(0.837)	(0.864)	(0.548)	(0.710)
Av. beef price in the municipio (real)	-4.564***	-0.662	1.414	-3.712	-1.923	-0.539***	0.113	0.339	-0.603	-0.324	0.691***	0.667
	(0.664)	(1.355)	(2.194)	(2.972)	(3.028)	(0.075)	(0.149)	(0.244)	(0.395)	(0.398)	(0.228)	(0.427)
Av. milk price in the municipio (real) * distance OPO		-0.164***	-0.186***	-0.054	-0.061		-0.029***	-0.031***	-0.013	-0.015	-0.022***	-0.019*
		(0.059)	(0.068)	(0.070)	(0.072)		(0.009)	(0.009)	(0.010)	(0.010)	(0.007)	(0.010)
Av. Beef price in the municipio (real) * distance OPO		-0.095***	-0.086**	0.002	-0.007		-0.018***	-0.016***	-0.006	-0.008	-0.019***	-0.013*
		(0.033)	(0.035)	(0.042)	(0.042)		(0.004)	(0.004)	(0.006)	(0.006)	(0.004)	(0.007)
Year fixed effects			✓	✓	✓			✓	✓	✓	✓	✓
Municipality trends				✓	✓				✓	✓		✓
Controls					✓					✓	✓	✓
Household fixed effects											✓	✓
Number of observations	745	745	745	745	740	745	745	745	745	740	740	740
Number of households	353	353	353	353	352	353	353	353	353	352	352	352
R-squared						0.06	0.077	0.077	0.124	0.144	0.316	0.318

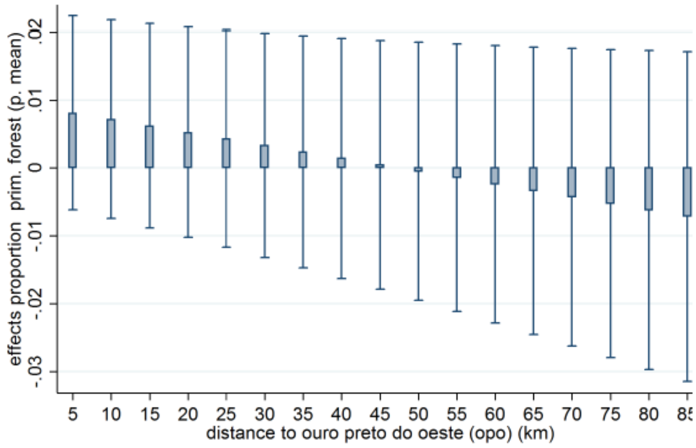
Notes: Values in parentheses denote clustered standard errors at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. For all specifications with no fixed effects controls include the average age of the heads of household, the average years of education of the heads of the household, lot size (ha, GIS estimate) and household size. For specifications with fixed effects, lot size is omitted as it is time-invariant.

Table 7: Secondary forest regression results - GLM and OLS

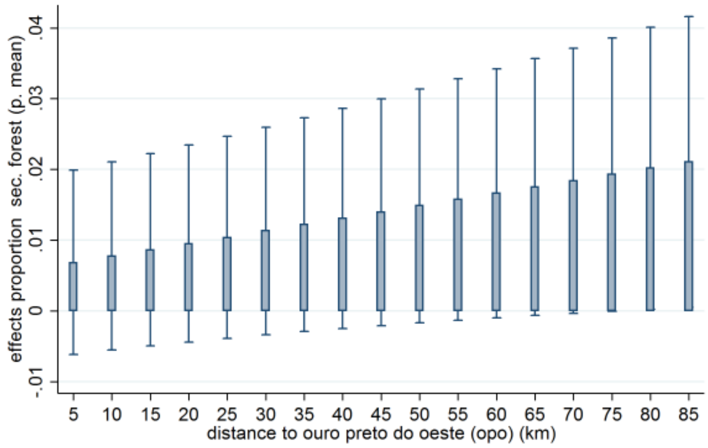
	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Distance to Ouro Preto do Oeste (OPO) (km)	0.006**	-0.039	-0.037	-0.076***	-0.089***	0.000**	-0.003	-0.003	-0.004**	-0.005**		
	(0.003)	(0.024)	(0.025)	(0.026)	(0.028)	(0.000)	(0.002)	(0.002)	(0.002)	(0.002)		
Av. milk price in the municipio (real)	-5.273***	-11.711***	-17.120***	-19.475***	-24.034***	-0.365***	-0.731***	-1.112***	-0.491	-0.737	-0.193	0.595
	(1.649)	(3.544)	(5.656)	(6.515)	(6.224)	(0.114)	(0.249)	(0.405)	(0.502)	(0.498)	(0.486)	(0.655)
Av. beef price in the municipio (real)	2.485***	1.717	-1.006	-20.243***	-22.060***	0.178***	0.063	-0.144	-1.105***	-1.297***	-0.907***	-1.254***
	(0.686)	(1.554)	(2.163)	(3.959)	(4.128)	(0.054)	(0.118)	(0.170)	(0.235)	(0.259)	(0.209)	(0.363)
Av. milk price in the municipio (real) * distance OPO		0.166**	0.189**	0.391***	0.420***		0.01	0.011*	0.019***	0.022***	0.016**	0.018**
		(0.084)	(0.087)	(0.101)	(0.107)		(0.006)	(0.006)	(0.007)	(0.007)	(0.007)	(0.008)
Av. Beef price in the municipio (real) * distance OPO		0.022	-0.005	-0.021	-0.008		0.003	0.001	0.001	0.002	0.002	-0.007
		(0.038)	(0.040)	(0.055)	(0.056)		(0.003)	(0.003)	(0.004)	(0.004)	(0.003)	(0.005)
Year fixed effects			✓	✓	✓			✓	✓	✓	✓	✓
Municipality trends				✓	✓				✓	✓		✓
Controls					✓					✓	✓	✓
Household fixed effects											✓	✓
Number of observations	745	745	745	745	740	745	745	745	745	740	740	740
Number of households	353	353	353	353	352	353	353	353	353	352	352	352
R-squared						0.025	0.026	0.029	0.115	0.16	0.096	0.123

Notes: Values in parentheses denote clustered standard errors at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.
For all specifications with no fixed effects controls include the average age of the heads of household, the average years of education of the heads of the household, lot size (ha, GIS estimate) and household size. For specifications with fixed effects, lot size is omitted as it is time-invariant.

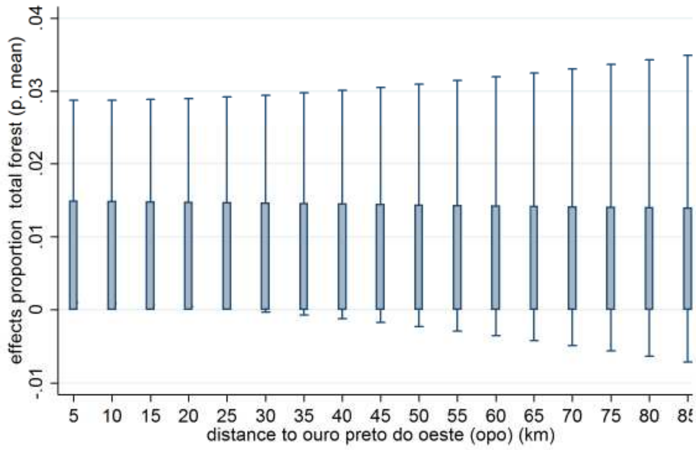
Figure 6: Marginal impacts - milk prices



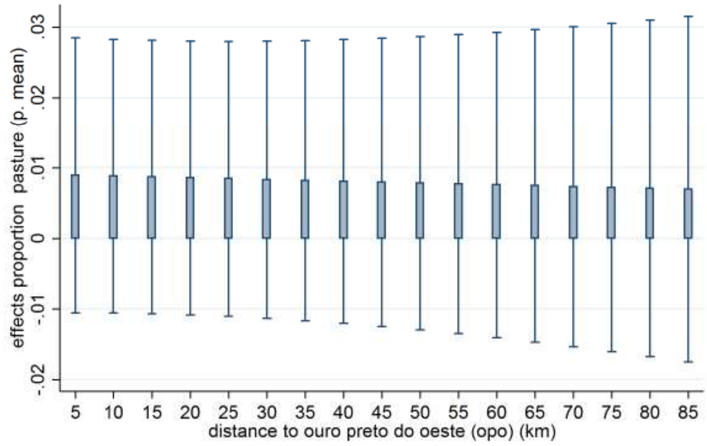
(a) Primary forest



(b) Secondary forest



(c) Total forest

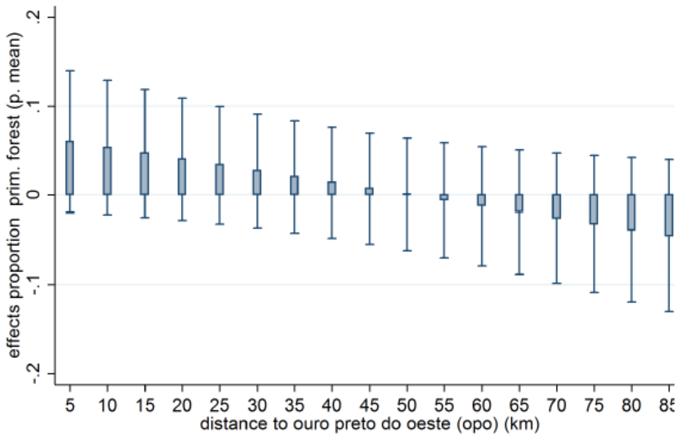


(d) Pasture

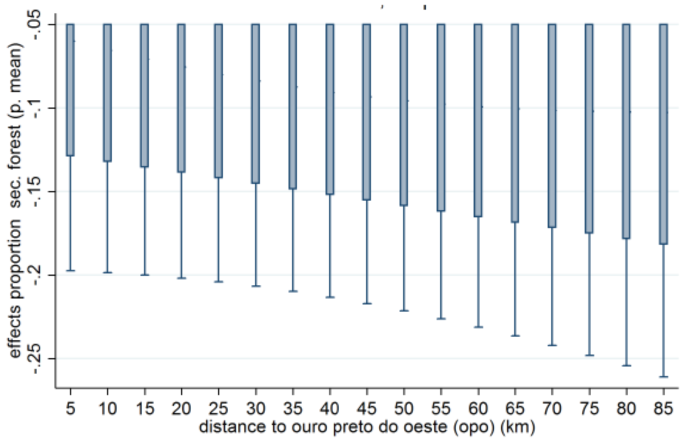
[a]

[a]Notes: The error bars denote the 95% confidence interval. As a result, when one extremity of the error bar is not visible, this implies that the result is statistically significant at the 5% level. For this part of the analysis, we re-scaled the milk price variable. In the main analysis the milk price variable is in reais. However, the increases in milk prices have often been small (3-5 cents in real terms over the sample period). As such, in order to make the scale of the figures more realistic, we have re-scaled the variable to centavos (cents) (i.e. we mutliplied the milk price variable by 100). Therefore, the coefficients in the graphs can be interpreted as a 1 cent increase in the price of milk leas to a $\beta * 100$ decrease in the proportion of land under the land-use cover. For instance, if for a given distance the marginal coefficient is -0.03, this suggests that a 1 cent increase in the real price of milk leads to a 0.03 (or 3 percentage point) decrease in the proportion of cover under the land-use.

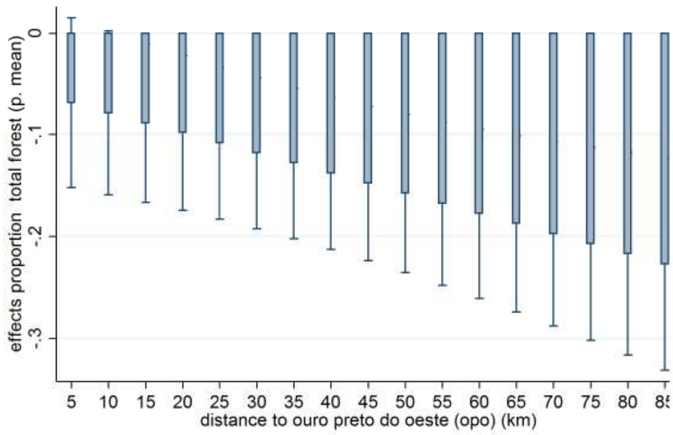
Figure 7: Marginal impacts - beef prices



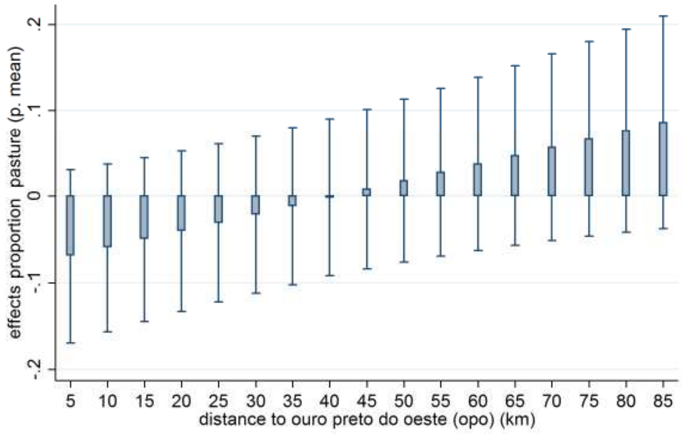
(a) **Primary forest**



(b) **Secondary forest**



(c) **Total forest**



(d) **Pasture**

[a]

[a]Notes: The error bars denote the 95% confidence interval. As a result, when one extremity of the error bar is not visible, this implies that the result is statistically significant at the 5% level. For this part of the analysis, we re-scaled the beef price variable. In the main analysis, our beef price variable is in 1,000 reais. However, in our sample over the period analyzed a most increases in beef prices are below 100 reais. As such, in order to make the scale of the figures more realistic, we have re-scaled the variable to 100 reais. Therefore, the coefficients in the graphs can be interpreted as a 100 dollar increase in the real price of beef leads to a $\beta * 100$ change in the proportion of land under the land-use cover. For instance, if for a given distance the marginal coefficient is -0.1, this suggests that a 100 dollar increase in the price of beef leads to -0.1 (or 10 percentage point) decrease in the proportion of cover under the land-use.

Table 8: **Further results - pasture and cattle stocking density by total initial forest cover**

	Pasture		Dairy cattle		Non-dairy cattle	
Variables	High	Low	High	Low	High	Low
Av. milk price in the municipio (real)	2.048	-0.773	0.147	3.409	14.473*	32.717
	(1.402)	(1.060)	(3.752)	(5.759)	(7.429)	(23.498)
Av. beef price in the municipio (real)	-0.908	0.093	0.251	-0.18	6.247	-3.158
	(0.766)	(0.613)	(2.173)	(3.179)	(7.511)	(12.496)
Av. milk price in the municipio (real) * distance OPO	-0.024	0.009	0.026	-0.034	0.031	-0.028
	(0.015)	(0.010)	(0.036)	(0.068)	(0.141)	(0.226)
Av. Beef price in the municipio (real) * distance OPO	0.029***	0.000	-0.026	0	-0.167	-0.043
	(0.011)	(0.010)	(0.030)	(0.054)	(0.107)	(0.178)
Year fixed effects	✓	✓	✓	✓	✓	✓
Municipality trends	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
Household fixed effects	✓	✓	✓	✓	✓	✓
Number of observations	372	368	366	366	365	365
Number of households	162	190	162	189	162	189
R-squared	0.234	0.146	0.094	0.069	0.065	0.041

Notes: Values in parentheses denote standard errors. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. Controls include the average age of the heads of household, the average years of education of the heads of the household and household size. Households in the "low" category have an initial forest cover equal or less than 21.3% of their total lot size.

Table 9: Further results - forest by total initial forest cover

	Primary forest		Secondary forest		Total forest	
Variables	High	Low	High	Low	High	Low
Av. milk price in the municipio (real)	0.724	0.461	0.926	0.766	1.65	1.227**
	(1.058)	(0.448)	(1.036)	(0.523)	(1.145)	(0.502)
Av. beef price in the municipio (real)	0.564	0.807***	-1.740***	-1.249***	-1.175*	-0.442
	(0.679)	(0.289)	(0.598)	(0.384)	(0.700)	(0.386)
Av. milk price in the municipio (real) * distance OPO	-0.013	-0.028***	0.031**	0.020**	0.018	-0.007
	(0.015)	(0.007)	(0.013)	(0.008)	(0.014)	(0.009)
Av. Beef price in the municipio (real) * distance OPO	-0.011	-0.014**	-0.013	0.005	-0.023**	-0.009
	(0.010)	(0.006)	(0.008)	(0.006)	(0.010)	(0.006)
Year fixed effects	✓	✓	✓	✓	✓	✓
Municipality trends	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
Household fixed effects	✓	✓	✓	✓	✓	✓
Number of observations	372	368	372	368	372	368
Number of households	162	190	162	190	162	190
R-squared	0.411	0.293	0.183	0.095	0.301	0.095

Notes: Values in parentheses denote standard errors. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively. Controls include the average age of the heads of household, the average years of education of the heads of the household and household size. Households in the "low" category have an initial forest cover equal or less than 21.3% of their total lot size.

10. APPENDIX TABLES

Table A1: Marginal effects - pasture and cattle density

		Pasture		Dairy	Non-Dairy
		GLM	OLS	OLS	OLS
Percentile	Dist. market (km.)	5	7	7	7
		Milk prices			
1	6.165	-0.928	0.891	1.706	23.282**
10	12.953	-1.001	0.874	1.692	23.243**
25	27.756	-1.062	0.838	1.663	23.159*
50	39.557	-1.171	0.809	1.639	23.092*
Mean	40.181	-1.196	0.807	1.638	23.089*
75	51.329	-1.299	0.779	1.616	23.026*
90	67.599	-1.455	0.739	1.584	22.933*
99	80.050	-1.685	0.708	1.558	22.861
		Beef prices			
1	6.165	0.205	-0.672	0.114	1.415
10	12.953	0.309	-0.540	0.038	0.594
25	27.756	0.397	-0.253	-0.127	-1.198
50	39.557	0.565	-0.026	-0.257	-2.609
Mean	40.181	0.604	-0.012	-0.264	-2.687
75	51.329	0.771**	0.205	-0.387	-4.016
90	67.599	1.038**	0.525	-0.566	-5.991
99	80.050	1.466***	0.762	-0.710	-7.527

Notes: Values in parentheses denote standard errors. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.

Table A2: Marginal effects - forest all

		Primary forest		Secondary forest		Total forest	
		GLM	OLS	GLM	OLS	GLM	OLS
Percentile	Dist. market (km)	5	7	5	7	5	7
Milk prices							
1	6.165	1.813***	0.784	-0.754**	0.705	1.745**	1.489**
10	12.953	1.897***	0.655	-0.827**	0.825	1.744**	1.480**
25	27.756	1.966***	0.374	-0.888**	1.088	1.739**	1.462*
50	39.557	2.090***	0.151	-0.999***	1.296	1.722*	1.447*
Mean	40.181	2.117***	0.138	-1.024***	1.309*	1.717*	1.447*
75	51.329	2.232***	-0.074	-1.129***	1.507*	1.690*	1.433*
90	67.599	2.403***	-0.388	-1.294***	1.800*	1.632	1.412
99	80.050	2.657**	-0.620	-1.557***	2.017**	1.505	1.397
Beef prices							
1	6.165	-0.429*	0.585	-0.946***	-1.295***	-1.234***	-0.710*
10	12.953	-0.480*	0.496	-0.963***	-1.340***	-1.325***	-0.844**
25	27.756	-0.524*	0.301	-0.977***	-1.438***	-1.400***	-1.138***
50	39.557	-0.607**	0.146	-1.001***	-1.516***	-1.539***	-1.370***
Mean	40.181	-0.626**	0.137	-1.006***	-1.521***	-1.570***	-1.384***
75	51.329	-0.709**	-0.010	-1.029***	-1.594***	-1.702***	-1.605***
90	67.599	-0.845**	-0.228	-1.063***	-1.704***	-1.905***	-1.931***
99	80.050	-1.073**	-0.389	-1.115***	-1.785***	-2.218***	-2.174***

Notes: Values in parentheses denote standard errors. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.

Table A3: Robustness checks - pasture and cattle stocking density

	Pasture				Non-dairy cattle			Dairy cattle		
Variables	No 2005	Levels	Logs	l. prices	No 2005	Logs	l. prices	No 2005	Logs	l. prices
Av. milk price in the municipio (real)	2.961**	209.869**	1.680*	5.277	16.065**	1.717	218.951	-0.275	3.879*	-18.638
	(1.231)	(84.032)	(0.928)	(5.870)	(7.319)	(1.846)	(137.651)	(3.941)	(2.278)	(28.970)
Av. milk price in the municipio (real) * dist. OPO (km)	0.008	-0.498	-0.103	0	0.098	0.651*	-0.338	0.005	-0.367	0.067
	(0.011)	(0.903)	(0.116)	(0.015)	(0.131)	(0.370)	(0.258)	(0.035)	(0.634)	(0.065)
Av. beef price in the municipio (real)	-1.581**	-92.713**	-1.211**	-2.717	-0.622	1.832	-33.879	-0.506	0.588	12.855
	(0.643)	(46.245)	(0.524)	(1.720)	(6.739)	(1.530)	(54.847)	(2.034)	(1.812)	(11.636)
Av. beef price in the municipio (real) * dist. OPO (km)	0.019*	1.352**	0.243**	0.097*	-0.068	-0.555	1.454	0.024	-0.31	-0.328
	(0.010)	(0.610)	(0.106)	(0.051)	(0.075)	(0.376)	(1.330)	(0.023)	(0.453)	(0.308)
Year fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipality trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Household fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Number of observations	456	740	740	384	451	671	375	452	612	377
Number of households	192	351	351	272	193	336	269	193	316	270
R-squared	0.178	0.158	0.077	0.135	0.027	0.067	0.123	0.074	0.103	0.098

Notes: Values in parentheses denote standard errors and these are clustered at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.
L. prices refers to the lagged prices specification. In this specification the coefficients on the average milk and beef prices refer to lagged milk and beef prices.
Controls include the average age of the heads of household, the average years of education of the heads of the household and household size.
In the Logs specification, the controls (including average municipal prices and distances) are all in logs. In this specification we also drop average education of the Household in this specification as there are large number of observations with 0 average years of education

Table A4: Robustness checks - forest cover

	Primary forest				Secondary forest				Total forest			
	No 2005	Levels	Logs	l. prices	No 2005	Levels	Logs	l. prices	No 2005	Levels	Logs	l. prices
Av. milk price in the municipio (real)	0.005	28.759	5.182***	5.593	0.541	6.551	-13.292***	-9.980*	0.546	35.31	1.845	-4.387
	(0.742)	(59.614)	(1.776)	(4.862)	(0.833)	(52.445)	(4.124)	(5.148)	(0.770)	(56.360)	(1.408)	(4.751)
Av. milk price in the municipio (real) * dis. OPO (km)	-0.024**	-1.305	-1.553**	-0.017**	0.015*	0.888	3.314***	0.007	-0.009	-0.417	-0.334	-0.01
	(0.010)	(0.821)	(0.631)	(0.007)	(0.009)	(0.591)	(0.813)	(0.014)	(0.010)	(0.794)	(0.490)	(0.013)
Av. beef price in the municipio (real)	0.802*	31.831	4.785**	-0.921	-1.131***	-53.388**	0.087	1.678	-0.329	-21.557	1.059	0.758
	(0.482)	(38.555)	(2.020)	(1.426)	(0.393)	(26.782)	(3.202)	(1.441)	(0.514)	(37.206)	(1.695)	(1.474)
Av. beef price in the municipio (real) * dis. OPO (km)	-0.007	-0.528	-1.020*	0.024	-0.011**	-0.732**	-2.100***	-0.056	-0.018**	-1.260**	-0.519	-0.032
	(0.007)	(0.552)	(0.614)	(0.043)	(0.005)	(0.362)	(0.719)	(0.043)	(0.009)	(0.533)	(0.414)	(0.043)
Year fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipality trends	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Household fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Number of observations	456	740	683	384	456	740	683	384	456	740	683	384
Number of households	192	351	332	272	192	351	335	272	192	351	346	272
R-squared	0.361	0.229	0.229	0.474	0.145	0.19	0.249	0.248	0.26	0.25	0.127	0.046

Notes: Values in parentheses denote standard errors and these are clustered at the household level. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.
L. prices refers to the lagged prices specification. In this specification the coefficients on the average milk and beef prices refer to lagged milk and beef prices. Controls include the average age of the heads of household, the average years of education of the heads of the household, lot size and household size.
In the Logs specification, the controls (including average municipal prices and distances) are all in logs. In this specification we also drop average education of the Household in this specification as there are large number of observations with 0 average years of education

Table A5: **Marginal effects - further results pasture and cattle**

Percentile	Dist. market (km)		Pasture		Dairy cattle		Non-dairy	
	High	Low	High	Low	High	Low	High	Low
				Milk prices				
1	7.532	6.165	1.870	-0.716	0.345	3.199	14.709*	32.545
10	18.265	11.968	1.617	-0.664	0.621	3.006	15.045*	32.386
25	29.522	25.193	1.352	-0.541	0.919	2.550	15.398*	32.012
50	42.325	38.311	1.050	-0.422	1.260	2.111	15.800	31.652
Mean	43.000	37.363	1.034	-0.429	1.273	2.138	15.817	31.675
75	57.020	46.818	0.704	-0.341	1.616	1.812	16.223	31.407
90	77.112	59.786	0.368	-0.222	2.021	1.370	16.706	31.043
99	81.736	77.211	0.121	-0.061	2.297	0.775	17.035	30.556
				Beef prices				
1	7.532	6.165	-0.691	0.090	0.052	-0.177	4.992	-3.425
10	18.265	11.968	-0.383	0.087	-0.226	-0.175	3.204	-3.670
25	29.522	24.787	-0.059	0.081	-0.525	-0.170	1.328	-4.250
50	42.325	36.525	0.309	0.075	-0.868	-0.165	-0.805	-4.808
Mean	43.000	37.363	0.329	0.075	-0.881	-0.165	-0.900	-4.772
75	57.020	45.420	0.731	0.071	-1.225	-0.161	-3.056	-5.187
90	77.112	58.577	1.140	0.065	-1.633	-0.156	-5.624	-5.749
99	81.736	77.103	1.441	0.056	-1.910	-0.149	-7.372	-6.505

Notes: Values in parentheses denote standard errors. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.

Table A6: Marginal effects - further results forest all

Percentile	Dist. market (km)		Primary forest		Secondary forest		Total forest	
	High	Low	High	Low	High	Low	High	Low
Milk prices								
1	7.532	6.165	0.628	0.291	1.160	0.892*	1.788	1.183**
10	18.265	11.968	0.492	0.135	1.494	1.007*	1.986*	1.142**
25	29.522	25.193	0.349	-0.235	1.843	1.280**	2.192*	1.045*
50	42.325	38.311	0.186	-0.590	2.241*	1.542**	2.428*	0.952
Mean	43.000	37.363	0.177	-0.569	2.263*	1.527**	2.441*	0.958
75	57.020	46.818	0.000	-0.832	2.698*	1.721**	2.698*	0.889
90	77.112	59.786	-0.181	-1.190	3.140**	1.985***	2.959*	0.795
99	81.736	77.211	-0.315	-1.671	3.466**	2.341***	3.152*	0.670
Beef prices								
1	7.532	6.165	0.485	0.721***	-1.835***	-1.216***	-1.351**	-0.495
10	18.265	11.968	0.371	0.643***	-1.972***	-1.186***	-1.601**	-0.544
25	29.522	24.787	0.252	0.456	-2.115***	-1.115***	-1.863***	-0.659**
50	42.325	36.525	0.117	0.277	-2.278***	-1.047***	-2.161***	-0.770***
Mean	43.000	37.363	0.110	0.288	-2.286***	-1.051***	-2.177***	-0.764***
75	57.020	45.420	-0.038	0.155	-2.464***	-1.001***	-2.503***	-0.846***
90	77.112	58.577	-0.188	-0.026	-2.645***	-0.932***	-2.834***	-0.958***
99	81.736	77.103	-0.299	-0.269	-2.779***	-0.840***	-3.078***	-1.108***

Notes: Values in parentheses denote standard errors. *, ** and *** denote statistical significance at the 10%, 5% and 1% level, respectively.

11. Technical Appendix (1): Details of the Model in Section 3

The first step is to assume a utility function of the form:

$U(Y, L_g, L_{f1}, L_{f2}, M, l)$ (A1)

This states that a household's utility depends on its level of consumption (*Y*), the amount of off-farm work (*M*), leisure (*l*) and different types of labour namely, general on-farm labour (L_g), labour required to convert primary forest to pasture (L_{f1}) and labour required to convert secondary forest to pasture (L_{f2}). The household's objective is to maximize A1 subject to four constraints. First, an income constraint:

$$p_y Y = (p_q - td)Q - (w_x + td)X + (w_m - td)\, M \qquad \text{(A2)}$$

where, *Y* represents the total amount of consumer goods, *Q* represents output, e.g. beef or milk, *X* denotes the quantity of inputs and *M* the amount of off-farm work. The unit cost of a consumer good is given by p_y, output price is p_q, while w_x and w_m represent, respectively, the market wage for a unit of off-farm labour and the market price of a unit of input. In addition, td is a linear transport cost, where *t* represents the transport cost for a given unit of distance and *d* represents the distance from the market. Since we impose linearity, this can be thought of as fuel costs, for instance. A2 states that the total expenditures on consumer goods ($p_y Y$) cannot exceed farm profits net of transport costs $\left((p_q - td)Q - (w_x + td)X\right)$ plus off-farm income net of transaction costs $(w_m - td)\, M$. In our setting, farm profits can be thought of the profits made from selling fattened cattle for beef or milk. The inputs could be, for instance, the number of calves and animal feed.

One innovation in the Fernandez-Cornejo et al. (2005) model is the introduction of a technology variable. In our model, farmers face a choice between three technologies, namely to remain where they are, intensify or extensify. Choice of technology is then defined by the following concave production function (constraint #2):

$Q = Q\left[X(\tau_t), L_g(\tau_t), P(\tau_t), \tau_t\right];\ \tau_t \geq 0$ (A3)

where both the quantity and the marginal productivity of each input depends on the technology adopted. As a result, total achievable cattle production is constrained by the chosen technology. For the purposes of this paper, we define the choice to extensify production as τ_1 and the choice to intensify as τ_2. The decision not engage in either of these processes occurs when $\tau_1 = \tau_2 = 0$. For the remainder of the model we will assume that:

$$\frac{\partial P}{\partial \tau_1} > \frac{\partial P}{\partial \tau_2};\ \frac{\partial X}{\partial \tau_2} > \frac{\partial X}{\partial \tau_1};\ \frac{\partial L_g}{\partial \tau_1} = \frac{\partial L_g}{\partial \tau_2} \qquad \text{(A4)}$$

In practice, we assume that with adoption of an extensive technology, increases in pasture area *P* are higher than with an intensive technology. Conversely, the increase in other inputs *X* are higher under an intensive technology than under an extensive technology. Finally, we assume that, in terms of general labour, L_g, the two technologies do not differ from one another. We further assume that both types of technology are mutually exclusive in that a household cannot intensify and extensify cattle production simultaneously ($\tau_1 * \tau_2 = 0$).

We then assume that total pasture area is given by the following equation (constraint #3):

$$P(L_{f1}, L_{f2}) = \bar{A} - \overline{F_1} + \beta_1 L_{f1} - \overline{F_2} + \beta_2 L_{f2}\,; \quad \overline{F_1} \geq \beta_1 L_{f1};\ \overline{F_2} \geq \beta_2 L_{f2};\ \overline{F_1} \geq 0;\ \overline{F_2} \geq 0 \qquad \text{(A5)}$$

where $\bar{A}$ represents the total (exogenous) lot area, and $\overline{F_1}$ and $\overline{F_2}$ denote the total exogenous initial amount of primary and secondary forest on the lot, respectively. Forest can be converted into new pasture land. Primary forest can be cleared with labour L_{f1} and each unit of this type of labour leads to a β_1 increase in pasture area. Similarly, for secondary forest, an additional unit of L_{f2} leads to a β_2 increase in the pasture area. We further assume that $\beta_2 > \beta_1$. In other words, we assume that it is cheaper to clear secondary forest than primary forest in that for a given input of labour a larger amount of land can be converted into pasture from secondary than primary forest.

The final constraint is a time constraint where it is assumed that:

$$T = L_g + L_{f1} + L_{f2} + M + l; M \geq 0; L_{f1} \geq 0; L_{f2} \geq 0; L_g > 0; l \geq 0 \quad \text{(A6)}$$

Thus, the total time of the household is allocated between a strictly positive amount of general labour (L_g), a non-negative amount of land clearing labour (L_{f1}, L_{f2}), a non-negative amount of off-farm labour (M) and a non-negative amount of leisure (*l*).

Plugging in the technology constraint and using the fact that pasture can be expressed as a function of labour, we can rewrite the first constraint (A3):

$$p_y Y = (p_q - td) Q[X(\tau_t), L_g(\tau_t), L_{f1}(\tau_t), L_{f2}(\tau_t), \tau_t,] - (w_x + td)X + (w_m - td)\, M \quad \text{(A7)}$$

We now write the Lagrangian as follows:

$$L = U(Y, L_g, L_{f1}, L_{f2}, M, l) + \lambda[(p_q - td) Q[X(\tau_t), L_g(\tau_t), L_{f1}(\tau_t), L_{f2}(\tau_t), \tau_t,] - (w_x + td)X + (w_m - td)\, M - pyY] - \mu[T - L_g - L_{f1} - L_{f2} - M - l] \quad \text{(A8)}$$

Take the first order derivatives:[25]

$$\frac{\partial L}{\partial Y} = \frac{\partial U}{\partial Y} - \lambda py = 0 \qquad (A9)$$

$$\frac{\partial L}{\partial l} = \frac{\partial U}{\partial l} - \mu = 0 \qquad (A10)$$

$$\frac{\partial L}{\partial X} = \lambda\left[(p_q - td)\frac{\partial Q}{\partial X} - w_x\right] = 0 \qquad (A11)$$

$$\frac{\partial L}{\partial L_{f1}} = \lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_1\right] - \mu \leq 0;\ \frac{\overline{F_1}}{\beta_1} \geq L_{f1} \geq 0, L_{f1}\left(\lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_1\right] - \mu\right) = 0; \quad (A12)$$

$$\frac{\partial L}{\partial L_{f2}} = \lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_2\right] - \mu \leq 0;\ \frac{\overline{F_2}}{\beta_2} \geq L_{f2} \geq 0, L_{f2}\left(\lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_2\right] - \mu\right) = 0; \quad (A13)$$

[25] Note: $\frac{\partial Q}{\partial L_{f1}} = \frac{\partial Q}{\partial P}\frac{\partial P}{\partial L_{f1}}$; take the derivative of $\frac{\partial P}{\partial L_{f1}}$ and we have β_1. Also: $\frac{\partial Q}{\partial L_{f2}} = \frac{\partial Q}{\partial P}\frac{\partial P}{\partial L_{f2}}$; take the derivative of $\frac{\partial P}{\partial L_{f2}}$ and we have β_2.

Note that, since $\beta_1 < \beta_2$, we have that if $\lambda\left[\left(p_q - td\right)\frac{\partial Q}{\partial P}\beta_2\right] - \mu < 0$, then by definition, $\lambda\left[\left(p_q - td\right)\frac{\partial Q}{\partial P}\beta_1\right] - \mu < 0$ will also hold. This implies two things. If the marginal productive effects of converting secondary forest into pasture do not compensate the hours worked by the household, then the household will not convert primary forest. In other words, if the optimal level of labour for conversion from secondary forest to pasture is 0 (i.e. $L_{f2} = 0$), then the same will hold for L_{f1}. The intuition behind this is simple. Since it is cheaper to convert secondary than primary forest, the household will only convert primary forest if there is no secondary forest remaining or if there is insufficient secondary to allow for the total desired pasture area. This suggests that we are likely to see more pronounced effects on reduction of secondary forest in contrast to primary forest.

$$\frac{\partial L}{\partial L_g} = \lambda\left[\left(p_q - td\right)\frac{\partial Q}{\partial L_g}\right] - \mu = 0; L_g > 0 \qquad (A14)$$

$$\frac{\partial L}{\partial M} = \lambda[w_m - td] - \mu = 0; M \geq 0, M(\lambda w_m - \mu) = 0 \qquad (A15)$$

Finally:

$$\frac{\partial L}{\partial \tau_t} = \lambda\left[\left(p_q - td\right)\left[\frac{\partial Q}{\partial X}\frac{\partial X}{\partial \tau_t} + \frac{\partial Q}{\partial L_g}\frac{\partial L_g}{\partial \tau_t} + \frac{\partial Q}{\partial P}\frac{\partial P}{\partial L_{f1}}\frac{\partial L_{f1}}{\partial \tau_t} + \frac{\partial Q}{\partial P}\frac{\partial P}{\partial L_{f2}}\frac{\partial L_{f2}}{\partial \tau_t} + \frac{\partial Q}{\partial \tau_t}\right] - (w_x + td)\frac{\partial X}{\partial \tau_t}\right] - \mu\frac{\partial L_{f1}}{\partial \tau_t} - \mu\frac{\partial L_{f2}}{\partial \tau_t} - \mu\frac{\partial L_g}{\partial \tau_t} \leq 0; \tau_t \geq 0, \tau_t\frac{\partial L}{\partial \tau_t} = 0 \qquad \text{(A16)}$$

Equation (A16) states that a household will adopt technology *t* if the benefits of adopting this technology exceed the costs of adoption. As such, if this equation is a strict inequality for *t*=1,2 , no technology will be adopted. Looking at the technology adoption decision separately, technologies 1 and 2 are adopted if:

$$\left(p_q - td\right)\frac{\partial Q}{\partial \tau_1} \geq (w_x + td)\frac{\partial X}{\partial \tau_1} + \frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} + \frac{\partial L_g}{\partial \tau_1}\right) \quad (A17)$$

$$\left(p_q - td\right)\frac{\partial Q}{\partial \tau_2} \geq (w_x + td)\frac{\partial X}{\partial \tau_2} + \frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_2} + \frac{\partial L_{f2}}{\partial \tau_2} + \frac{\partial L_g}{\partial \tau_2}\right) \quad (A18)$$

Note from the first-order conditions (A9, A10 and A15) that, for non-zero quantities of off-farm labour we have:

$$\frac{\mu}{\lambda} = w_m - td = \left[\left(p_q - td\right)\frac{\partial Q}{\partial L_g}\right] \; (A17)$$

As a result, if we assume that $\frac{\partial Q}{\partial L_g}$ is the same under τ_1 and τ_2, we have that, the furthest away the households are from the market, the lowest $\frac{\mu}{\lambda}$ but the highest input costs $(w_x + td)$. This result implies that, if extensification and intensification affect revenues in the same way, the further a household is from the market the more likely it is to extensify. Suppose for simplicity that $\left[\frac{\partial Q}{\partial \tau_1}\right] = \left[\frac{\partial Q}{\partial \tau_2}\right]$, i.e. a one-unit increase in adoption of a more intensive technology leads to the same output increase as a one-unit output increase from adopting an extensive technology. The household will adopt a more extensive production system if:

$$(w_x + td)\frac{\partial X}{\partial \tau_1} + \frac{\mu}{\lambda}\ \frac{\partial L_{f1}}{\partial \tau_1} + \frac{\mu}{\lambda}\frac{\partial L_{f2}}{\partial \tau_1} + \frac{\mu}{\lambda}\frac{\partial L_g}{\partial \tau_1} \le (w_x + td)\frac{\partial X}{\partial \tau_2} + \frac{\mu}{\lambda}\ \frac{\partial L_{f1}}{\partial \tau_2} + \frac{\mu}{\lambda}\frac{\partial L_{f2}}{\partial \tau_2} + \frac{\mu}{\lambda}\frac{\partial L_g}{\partial \tau_2} \quad (A18)$$

We can rearrange this such that:

$$\frac{\mu}{\lambda}\ \left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} + \frac{\partial L_g}{\partial \tau_1} - \frac{\partial L_{f1}}{\partial \tau_2} - \frac{\partial L_{f2}}{\partial \tau_2} - \frac{\partial L_g}{\partial \tau_2}\right) \le (w_x + td)\left(\frac{\partial X}{\partial \tau_2} - \frac{\partial X}{\partial \tau_1}\right) \ \ (A19)$$

Since we assumed at the beginning that $\frac{\partial L_g}{\partial \tau_1} = \frac{\partial L_g}{\partial \tau_2}$ these terms disappear. And, since $\frac{\mu}{\lambda}$ is decreasing in distance to market and $(w_x + td)$ is increasing in distance to market, then the further away the household is from the market, the more likely it is to adopt an extensive technology, given that the opportunity costs of working off-farm are lower (due to higher transportation costs), the costs of purchasing inputs are higher (again due to higher transportation costs), and extensive production systems are assumed to be more labour-intensive as opposed to more intensive in other inputs.

12. Technical Appendix (2): Adding a PES to the Model in Section 3

First, we assume that for each additional unit of forest, primary or secondary, in the lot, the household is offered a subsidy or PES of s to keep the forest standing rather than convert it to pasture. Our set of constraints is then augmented with a fifth constraint in the form of a deforestation function:

$F_1 = \overline{F_1} - \beta_1 L_{f1};\ F_2 = \overline{F_2} - \beta_2 L_{f2}$ (A20)

The full income constraint can be rewritten as:

$p_y Y = (p_q - td)Q[X(\tau_t), L_g(\tau_t), L_{f1}(\tau_t), L_{f2}(\tau_t), \tau_t,] - (w_x + td)X + (w_m - td)\ M + s(\ \overline{F_1} - \beta_1 L_{f1} + \overline{F_2} - \beta_2 L_{f2})$ (A21)

The resulting Lagrangian is:

$$\begin{aligned} L = U(Y, L_g, L_{f1}, L_{f2}, M, l) \\ + \lambda[(p_q - td)Q[X(\tau_t), L_g(\tau_t), L_{f1}(\tau_t), L_{f2}(\tau_t), \tau_t,] - (w_x + td)X + (w_m - td)\ M \\ + s(\ \overline{F_1} - \beta_1 L_{f1} + \overline{F_2} - \beta_2 L_{f2}) - pyY] - \mu[T - \ L_g - L_{f1} - L_{f2} - M - l]\ \ (A22) \end{aligned}$$

The first-order conditions are similar to those derived in Technical Appendix (2), with the exception of:

$$\frac{\partial L}{\partial L_{f1}} = \lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_1\right] - s\beta_1 - \mu \le 0;\ \ \frac{\overline{F_1}}{\beta_1} \ge \ L_{f1} \ge 0, L_{f1}\left(\lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_1\right] - s\beta_1 - \mu\right) = 0;\ \ (A23)$$

$$\frac{\partial L}{\partial L_{f2}} = \lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_2\right] - s\beta_2 - \mu \le 0;\ \ \frac{\overline{F_2}}{\beta_2} \ge \ L_{f2} \ge 0, L_{f2}\left(\lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_2\right] - s\beta_2 - \mu\right) = 0;\ (A24)$$

As before, since $\beta_1 < \beta_2$, we have that if $\lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_2\right] - s\beta_2 - \mu < 0$, then by definition, $\lambda\left[(p_q - td)\frac{\partial Q}{\partial P}\beta_1\right] - s\beta_1 - \mu < 0$ will also hold. For a non-zero level of conversion of forest (primary or secondary), a household with the option of participating in a PES scheme would compare the marginal benefits of converting forest to pasture against the marginal cost of household time required to clear forest plus income from the PES scheme.

The last first-order condition to change is the technology adoption decision (A16) which becomes:

$$\frac{\partial L}{\partial \tau_t} = \lambda\left[(p_q - td)\left[\frac{\partial Q}{\partial X}\frac{\partial X}{\partial \tau_t} + \frac{\partial Q}{\partial L_g}\frac{\partial L_g}{\partial \tau_t} + \frac{\partial Q}{\partial P}\frac{\partial P}{\partial L_{f1}}\frac{\partial L_{f1}}{\partial \tau_t} + \frac{\partial Q}{\partial P}\frac{\partial P}{\partial L_{f2}}\frac{\partial L_{f2}}{\partial \tau_t} + \frac{\partial Q}{\partial \tau_t}\right] - (w_x + td)\frac{\partial X}{\partial \tau_t} - s\left(\frac{\partial L_{f1}}{\partial \tau_t} + \frac{\partial L_{f2}}{\partial \tau_t}\right)\right] - \mu\frac{\partial L_{f1}}{\partial \tau_t} - \mu\frac{\partial L_{f2}}{\partial \tau_t} - \mu\frac{\partial L_g}{\partial \tau_t} \leq 0; \tau_t \geq 0, \tau_t\frac{\partial L}{\partial \tau_t} = 0 \qquad (A25)$$

The household will adopt technology t if the benefits of adoption exceed the costs, with the latter including forgone revenue from the PES scheme, $s(\frac{\partial L_{f1}}{\partial \tau_t} + \frac{\partial L_{f2}}{\partial \tau_t})$), as well as the additional input costs, ($(w_x + td)\frac{\partial X}{\partial \tau_t}$), and the household's valuation of time,($\mu\frac{\partial L_{f1}}{\partial \tau_t} - \mu\frac{\partial L_{f2}}{\partial \tau_t} - \mu\frac{\partial L_g}{\partial \tau_t}$)) .

Technologies 1 and 2 are adopted if:

$$\left[(p_q - td)\left[\frac{\partial Q}{\partial \tau_1}\right]\right] \geq (w_x + td)\frac{\partial X}{\partial \tau_1} + s\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1}\right) + \frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} + \frac{\partial L_g}{\partial \tau_1}\right) \ (A26)$$

$$\left[(p_q - td)\left[\frac{\partial Q}{\partial \tau_2}\right]\right] \geq (w_x + td)\frac{\partial X}{\partial \tau_2} + s\left(\frac{\partial L_{f1}}{\partial \tau_2} + \frac{\partial L_{f2}}{\partial \tau_2}\right) + \frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_2} + \frac{\partial L_{f2}}{\partial \tau_2} + \frac{\partial L_g}{\partial \tau_2}\right) \ (A27)$$

Assume again that $\left[\frac{\partial Q}{\partial \tau_1}\right] = \left[\frac{\partial Q}{\partial \tau_2}\right]$, i.e. a one-unit increase in adoption of a more intensive technology leads to the same output increase as a one-unit output increase from adopting an extensive technology. The household will adopt a more extensive production system if:

$$(w_x + td)\frac{\partial X}{\partial \tau_1} + \frac{\mu}{\lambda}\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\mu}{\lambda}\frac{\partial L_{f2}}{\partial \tau_1} + \frac{\mu}{\lambda}\frac{\partial L_g}{\partial \tau_1} + s\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1}\right) \leq (w_x + td)\frac{\partial X}{\partial \tau_2} + \frac{\mu}{\lambda}\frac{\partial L_{f1}}{\partial \tau_2} + \frac{\mu}{\lambda}\frac{\partial L_{f2}}{\partial \tau_2} + \frac{\mu}{\lambda}\frac{\partial L_g}{\partial \tau_2} + s\left(\frac{\partial L_{f1}}{\partial \tau_2} + \frac{\partial L_{f2}}{\partial \tau_2}\right) \ (A28)$$

Rearranging gives:

$$\frac{\mu}{\lambda}\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} - \frac{\partial L_{f1}}{\partial \tau_2} - \frac{\partial L_{f2}}{\partial \tau_2}\right) + s\left(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} - \frac{\partial L_{f1}}{\partial \tau_2} - \frac{\partial L_{f2}}{\partial \tau_2}\right) \leq (w_x + td)\left(\frac{\partial X}{\partial \tau_2} - \frac{\partial X}{\partial \tau_1}\right) \ (A29)$$

Since $\frac{\mu}{\lambda}$ is decreasing and $(w_x + td)$ is increasing in distance to market, respectively, the further away the household is from the market, the more likely it is to adopt an extensive technology, given that the opportunity costs of working off-farm are lower, the costs of purchasing inputs are higher, and extensive production systems are assumed to be more labour-intensive as opposed to more intensive in other inputs. The difference this time, however, is that the option of volunteering into a PES scheme would make technology adoption less desirable for any technology that requires land conversion since the revenue from a PES is forgone once forest is converted into pasture. That said, the PES would promote an intensive over an extensive technology: it would make (A29) harder to satisfy because by definition the term $(s(\frac{\partial L_{f1}}{\partial \tau_1} + \frac{\partial L_{f2}}{\partial \tau_1} - \frac{\partial L_{f1}}{\partial \tau_2} - \frac{\partial L_{f2}}{\partial \tau_2}))$ on the left-hand side is always positive. Moreover, the higher is the payment *s* the less likely it is satisfied holding all else equal.

13. Technical Appendix (3): Creating the Dataset

Observations kept

In order to construct the dataset we use, we undertook a number of steps. We only kept observations with a household identifier for which the data are non-empty for at least some of the variables of interest. This left us with 1,437 observations.

We then removed households that report living in different municipalities (91 observations), households that have different values for distance to Ouro Preto do Oeste (47 observations) and households for which this variable is missing (62 observations). Following this, we also removed households added to the sample in 2009 (327 observations) since we use a fixed effects estimator as the main estimation method and all of the observations from 1996 (162 observations) since beef prices are not available in 1996. We are then left with a final sample of 746 observations.

Created variables and data transformations

Our analysis relies upon variables which had to be created using the existing data. These variables are constructed as follows:

1) Non-dairy cattle – This variable is defined as the total amount of cattle on the lot minus the total number of dairy cattle on the lot

2) Total forest cover – Sum of total primary forest (GIS) and secondary forest (GIS)

3) Proportion of land under pasture, primary forest, total forest and secondary forest – Total land under the land-use divided by total (GIS) lot size

4) Dairy and non-dairy cattle stocking densities – Total number of (dairy or non-dairy) cattle in the lot divided by total area of the lot net of primary forest (GIS estimates)

5) Deflators – Real prices are given for the prices of milk but not for beef. We thus divided the real price of milk in the wet season by its nominal price. When not available, the average municipal deflator is used.

6) Real Beef prices - Multiply the nominal beef price by the calculated deflator.

7) Milk and beef prices – The real wet season milk prices and beef prices used are calculated using the unweighted municipal average of the reported prices in a given municipality in a given year. Note, for the purposes of the paper the beef price variable is further transformed by dividing the beef price by 1000. The reason for doing this is that it makes the interpretation of the coefficients more straightforward.