WAS VON THÜNEN RIGHT?

CATTLE INTENSIFICATION AND DEFORESTATION IN BRAZIL[1]

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DRAFT – September 2016

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, however, differ 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

JEL classification: Q12, Q15, Q23, Q24

[1] Acknowledgements: We wish to thank the authors of the dataset (Caviglia-Harris, J. L., Roberts, D. and Sills, E. O.) as well as the ICPSR (the distributor) for making this dataset publicly available. We also thank David Simpson and participants at the Laboratoire d'Economie Forestière Biannual Workshop for useful comments.

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1. INTRODUCTION

Recent 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 Amazon, the setting for our paper, crop expansion as well as expanding cattle populations and pasture areas 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). Indeed between 1975 and 2006, this pattern is observed in 'agriculturally consolidated' areas in the south of Brazil but not in Amazon forest frontier areas where intensification occurred alongside expansion (Barretto et al., 2013).[4]

We examine whether these patterns of intensification and expansion at the frontier are consistent with the land rent framework, originated by von Thünen (1966), in which location and distance to markets is a key determinant of rents. Closer to market, farmers bear lower costs in getting their products to market and since they make higher profits, rent is higher (Angelsen, 1999; 2010; Chomitz et al., 2006). Rent thus declines with distance, and as land values decrease land uses become more extensive. Agricultural intensification and forest clearing for agriculture can be framed as investments, requiring land, labour, and capital. The agricultural frontier is located where agricultural expansion is no longer profitable. On the basis of this theory, we hypothesise that the closer a rural household is to market, the more likely it will intensify cattle production rather than expand pasture in response to rising demand for beef and milk. A corollary is that the further away a household is from market, the more likely it will expand pasture and hence, deforest rather than intensify in response to rising demand.

Our hypothesis is put to the test in a sample of rural households with privately-held lots in the state of Rondônia, which experienced the most extensive and rapid land transformation of all Brazilian states between the 1980s and early 2000s (Alves, 2002). In earlier work, Sills and Caviglia-Harris (2008) find that distance to market explains about one third of the variation in farm value. Also consistent with the von Thünen framework, cattle stocking rates, reflecting agricultural investment, are positively and significantly correlated with farm value. This implies that where land rents are greater, higher rates of cattle intensification are more likely than in areas where rents are smaller. Drawing upon data collected over four waves between 1996 and 2009, our empirical analysis is the first, to our knowledge, to test whether distance to market and by extension von Thünen's framework, has causal impacts on agricultural productivity. We are also able to explore whether there is any evidence for land sparing alongside intensification and the reduction of cultivated areas, in doing so test for the patterns observed by Barretto et al. (2013) albeit at the micro scale.

In general, empirical research on deforestation at the household scale using longitudinal data remains relatively rare. Also rare are analyses of tropical deforestation that differentiate between primary and secondary forest. Combining these, as is typical in the literature, overlooks important differences with respect to their relative ecological values as well as the dynamics of deforestation and land-use change (see Vincent, 2016). Indeed, little is known about the effects of prices, their interaction with markets and how these drive the intensification of agriculture at the household scale. Closest to our study is Caviglia-Harris (2005) who examines the first two waves of our dataset

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

in order to analyse the determinants of land use intensification and cattle accumulation. She finds significantly less deforestation and smaller cattle herds with increasing distance to market but no effect on cattle stocking density. However, these results must be treated with some degree of caution given the small size of the sample, a reliance on two waves of data, and a failure to account for household heterogeneity (fixed effects), and municipality trends in the estimation framework. In subsequent work, Caviglia-Harris and Harris (2011) use the four waves of the sample and adopt a fixed-effects framework to investigate how settlement design affects land use and deforestation. They find that the price of milk decreases the rate of deforestation but increases the proportion of the plot deforested. Yet, beef prices are neglected and no distinction is made between primary and secondary forest. Also, how price changes interact with distance to market is not examined.

With 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), the von Thünen framework arguably provides a useful theoretical basis for improved understanding of patterns of land use at the micro-scale.[5] Empirical, theoretical and policy-driven research on deforestation often uses distance to market as a measure of location. While the predictions of von Thünen's framework over time have been studied theoretically in a forest setting, e.g. Angelsen (2007), whether and how the concentric circles predicted by theory get shifted over time have received less attention in empirical work. Work by Ahrends et al. (2010) gets as far as mapping out at least three theoretically 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 solely on land use and biophysical data and the crude identification of local land uses. As such, what drove these observed shifts in terms of the immediate causes of deforestation such as changes in input and output prices could not be empirically tested.

To examine how households respond to rising prices given their distance to the nearest market, we apply a fixed effects model to our dataset. Since a household's distance to market does not vary over the sample period for the majority of our sample, it cannot be included in a model with household fixed effects. We circumvent this by interacting distance to market with a variable that is expected to have an impact on the household's decision of whether to invest in beef and milk production: municipality-level prices for beef and milk. The analysis then focuses on how households respond to changing demand, conditional on their location, in terms of the changes in the proportion of the lot that under pasture and forest (primary, secondary, total) area measured by GIS. We also examine impacts on cattle stocking densities that are reported in household surveys.

In order to help identify the causal effect of distance to market and commodity prices on land use change and cattle stocking densities, we apply the following in our estimation framework. First, year fixed effects are included to deal common shocks in different waves (such as weather or policy shocks). Second, municipality-specific linear time trends are included to help capture differential trends in the variables of interest at the municipality level, e.g. settlement dates. We include municipality trends to capture both the heterogeneous trends as well as other local factors at the municipality scale that might affect outcomes, e.g. development of local infrastructure, local economic growth, market integration, and the development of agricultural institutions. Third, a set of time-varying household controls are added, including lot and household size. Fourth, household fixed effects are included in order to deal with time invariant unobserved heterogeneity, like slope

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

and soil quality. Finally, since our land-use dependent variables are in proportions, we also repeat the analysis using a GLM estimator with a logit link.

With increasing distance to market, our results first suggest that lots contain higher proportions of primary but lower proportions of secondary forest. Consistent with theory, we find some evidence of significant increases in pasture area in lots located further away from the market relative to those closer to the market, driven by rising demand for beef. Interestingly, we find some evidence of the reverse pattern in the case of milk. Regarding total forest, rising prices are found to cause significantly lower rates of forest cover, with a more pronounced impact identified in lots located further away from the market. This result is much stronger for beef than for milk and mainly affects secondary forest. For primary forest, an increase in beef prices appears to have an insignificant effect on forest cover in lots close to the market but leads to a negative and significant effect on forest cover in lots found further away from market. This last result suggests limited support for 'land sparing' in lots closer to market. There is also limited evidence for the intensification of cattle production closer to market yet this is not conclusive and would need to be set against strong evidence for the conversion of secondary forest in the same lots. Further analysis suggests evidence for rising prices inducing higher rates of deforestation in lots located a greater distance from market and for an 'endowment effect', in which households with larger initial forest endowments are found to deforest more than those with smaller endowments.

In the remainder of the paper, Section 2 presents background on cattle ranching in the Brazilian Amazon and the state of Rondônia, which is followed by a the land rent framework in Section 3 and a description of the data and some summary statistics, in Section 4. Section 5 elaborates our hypothesis and outlines our empirical approach while Section 6 presents our results. Discussed further in Section 7, we first present the main results and some robustness checks before examining evidence for the role of forest endowments in patterns of land use change.

2. BACKGROUND

Large-scale colonization of the Amazon began in the 1960s (Bowman et al., 2011). 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. According to Steiger (2006) between 1994 and 2006 alone, overall domestic consumption of cattle products per capita increased by 13%. 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).

Taken together, these conditions have contributed to a cattle herd increase, 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 between the 1960s and 1991, Rondônia grew from having a trivial cattle herd and a beef self-reliance rate (beef production relative to beef consumption[6]) of only 6%, to having the second biggest cattle herd in the region and a self-reliance rate of 190% by 1991. Since, this trend has continued. According to Barros et al. (2002), herd size in Rondônia has tripled between 1990 and 2000, from 1.7 million to 5.6 million heads of cattle. This expansion in the

[6] Faminow and Vosti (1997) provide a very rough idea of production and consumption in the absence of trade.

cattle herd, however, came at the expense of large scale deforestation, with deforested area increasing from just 2% in 1977 to over 60% in 2005 (Caviglia-Harris et al., 2009).

The potential of cattle intensification to help reduce deforestation has received attention from researchers and policymakers at least since the work of Angelsen and Kaimowitz (2001). As highlighted by McManus et al. (2016), there has been a substantial increase in productivity in Brazilian cattle production since the 1990s. Recently, a number of authors have suggested that an intensification of cattle need not be synonymous with more deforestation (Vale, 2015). However, whether this will be enough significantly slow deforestation in the Amazon remains unknown.

3. LAND RENT FRAMEWORK AND HYPOTHESES

The land rent framework, originally developed by von Thünen (1966) and applied to rural households at the forest frontier by Angelsen (1999) and others since, implies that land uses become more extensive as distance to market increases. Closer to market, the transportation of agricultural commodities is cheaper thus raising rents. However, inputs to agricultural production particularly land and labour may be more costly, the latter due to higher opportunity costs of labour. Since forest conversion and subsequent pasture expansion requires both of these inputs, there may be incentives to intensify the closer the household is located to market. Intensification is both less labour and land intensive than forest conversion for pasture expansion yet may be more capital intensive.

As described by Caviglia-Harris (2004) and Caviglia-Harris et al. (2010), many of the privately-held lots in our setting were established via government-sponsored settlement programmes in the 1970s. Households initially converted forest to crops before purchasing cattle and converting cropland to pasture. Increasingly households moved towards the direct conversion of forest to pasture. Given the dominance of pasture and cattle ranching in terms of land use and household incomes (see Section 4), we consider three different land uses: I = intensive cattle production; E = extensive cattle production; and, F = forest. Following Angelsen (2007), land rent, *r*, of the different land uses (denoted by subscript *i*) is a declining function of distance to market, *d*:

$$r^i(d) = p^i y^i - wl^i - qk^i - v^i d; \qquad i = I, E, F \qquad (1)$$

where beef and milk are sold in the market at price *p*; we assume $p^I = p^E$, based on the fact that in our setting no subsidies exist for beef and milk derived from intensive cattle production. There are also no incentives for forest protection, e.g. in the form of a payments for environmental services (PES) scheme, received by any of our sampled households. Yet, they may derive some value from standing forests, e.g. from non-timber forest products. In addition, Brazil's Forest Code stipulates that private landowners in the Legal Amazon are required to maintain 80 percent of their land under forest cover.[7] Cattle production per ha is given as *y* and the labour and capital input required per ha are *l* and *k*, with wage, *w*, and annual capital costs, *q*. Transport costs are denoted *v*.

The rent curves and associated land use 'zones ', within von Thünen's concentric circles, are shown in Figure 1. The border between intensive and extensive cattle production defines the intensive margin while that between extensive cattle production and forest defines the extensive margin.

[7] 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).

Both borders are shown in bold in Figure 1, marking the points where the rent curves of different land uses cross.

Figure 1 HERE

Holding all else in equation (1) equal, an increase in milk or beef prices, represented by $p^{l,E}$, will raise $r^{l,E}$ and push out both the r^{l} and r^{E} curves and hence, the two borders representing the cattle margins. For a lot located on or near the intensive margin, a price rise is expected to raise the likelihood of more intensive cattle production vis-à-vis extensive production. For one located further away, nearer to the extensive margin, we expect to observe higher rates of deforestation and expansion of cattle pasture. Although a straightforward prediction based on a very simple model,[8] there is empirical support for distinct patterns of concentric waves expanding through time and space that accord with von Thünen (e.g. Ahrends et al., 2010). In sum, we hypothesise rising demand for beef and milk will closer to market, holding all else equal, lead to:

- Higher rates of intensification (proxied by cattle stocking density of dairy and non-dairy cattle[9])
- Lower rates of pasture expansion (GIS)
- Lower rates of deforestation (primary forest, secondary forest, total forest; all GIS)

A corollary is that the further away from market, we would expect rising demand for beef and milk to cause lower rates of intensification and higher rates of pasture expansion and deforestation.

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 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 is used to cross-check the accuracy of estimates. As shown in Table 1, households have large average lot sizes. 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. 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 2009, the sample was expanded again to include over 200 additional lots. However, this issue is likely to be less salient for our analysis since, given our use of fixed effects, which implies dropping the households added to the dataset in 2009. In Section 5, we explain how we address the lots added to the sample in 2005.

TABLE 1 HERE

[8] Missing particularly is an explicit consideration of household dynamics with respect to other external changes, particularly technological change and market integration (Angelsen (2007) gives a good overview of the issues and some relevant studies).

[9] This variable divides the total number of dairy and non-dairy cattle by the total plot area, net of forest area.

From Table 1, we make a number of observations. First, average family size in our dataset is just over six members per household, mostly adults. The average number of years of education of the household heads is 3.24 years. Second, the average household in the sample is approximately 40 km away from Ouro Preto do Oeste. This distance ranges from 0 to 82 km, which is relatively small in the context of the Amazon. Third, we note that the three largest sources of income are milk, beef and perennial crops. Milk, in particular, is the largest source of income for the sampled households. As such, prices of milk and beef are likely to have important consequences for households' agricultural decisions. Fourth, as noted households own large lots (on average, 72 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.

We begin our analysis of how households responded to changes in milk and beef prices given the distance of their lots to the center of Ouro Preto do Oeste,[10] by highlighting some of the trends in prices over the sample period. Figure 2 depicts the price trends of these two commodities over the sample period. Both show a very pronounced increase in prices, partly driven by strong domestic and international demand in cattle-related products. The local polynomial of real milk prices (on the left y-axis), shows an average increase from about 0.19 reais (19 cents) per litre to about 0.24 reais (24 cents) per litre, which implies an increase in real prices of about 25% over 13 years. 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.[11] In other municipalities, increases during the 2000-2009 period ranged from 2-4 cents per litre. For beef, data were not collected in 1996, although the price seems to follow a similar trend, with an increase of just over 20% over a nine-year period. The biggest increase in beef prices in any municipality between 2000 and 2009 was 122 reais per steer. In others, increases ranged from about 42-111 reais, with the unweighted[12] average increase in real beef prices being 80 reais.

FIGURE 2 HERE

Figures 3, 4 and 5 depict some general time trends in land-use change and cattle stocking density as well showing how these variables change with distance to market. A number of patterns emerge. First, as can be seen in Figure 3 there is a consistent trend of deforestation throughout our sample period, which led to the average proportion of total forest cover decreasing substantially among the households in our dataset. A second aspect which is highlighted in the right-hand-side graph of Figure 3 is that, while the trend is non-linear, there seems to be quite a clear pattern of greater forest cover in lots which are further away from the centre of Ouro Preto do Oeste.

FIGURE 3 HERE

Figure 4 highlights the evolution of land under pasture and the number of cattle (disaggregated by type) on the lot over the sample period. The trends are quite clear and suggest a very sharp increase in the land area under pasture and an associated increase in the number of cattle in the lot, although the increase is mostly driven by increases in non-dairy cattle. 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

[10] Home to about 25-30,000 people, Ouro Preto do Oeste is the same town that was used to estimate distance to market by Sills and Caviglia-Harris (2008).

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

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

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 have a smaller number of cattle. Interestingly, the pattern on the number of cattle is much more pronounced for non-dairy cattle than for dairy cattle.

FIGURE 4 HERE

Figure 5 shows the cattle stocking density, defined as the number of cattle in the lot divided by total lot size net of primary forest. The pattern suggests an increase in cattle stocking density over time, more so for non-dairy cattle. In terms of the distance to market, we note that, on average, there is a decrease in the cattle stocking density as we move away from the market, although this relationship does not seem to be linear.

FIGURE 5 HERE

Nevertheless, while these descriptive trends are interesting, we cannot infer whether the distance to market is in effect causing the observed patterns in land use and cattle stocking density. Also, they tell us little about whether there is any variation in household response to rising prices given distance to market and expected patterns of cattle intensification and pasture expansion.

5. METHODOLOGY AND ESTIMATION

In order to test our hypotheses, we estimate the following equation using the following fixed effects model:

$$Y_{it} = \beta \boldsymbol{X}_{it} + \Omega_m t + \varphi p_{cmt} + \delta p_{cmt} * dist_i + \alpha_i + \mu_t + \varepsilon_{it} \qquad (2)$$

Equation (2) models the dependent variable *Y* for household *i* at time *t* as a function of a set of household specific covariates $\boldsymbol{X}_{it}$, a municipality-specific time trend ($\Omega_m t$), which accounts for common trends across households in a municipality.[13] We also include household fixed effects (α_i) to control for time-invariant individual heterogeneity, and year fixed effects μ_t, which control for common shocks affecting all households in a given year. Finally, regarding the variables of interest, we estimate the coefficients on the price of commodity *c* (milk and/or beef)[14] in municipality *m* at time *t* (φp_{cmt}) and its interaction with the distance to market ($\delta p_{cmt} * dist_i$). Note, in order to make the coefficients comparable, the price of beef was divided by 1,000.

We estimate this model for proportion of land under pasture, cattle stocking density (dairy and non-dairy), and proportion of forest cover (primary, secondary and total).[15] According to the theory, 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

[13] Different municipalities have been settled at different points in time and, as shown by Caviglia-Harris et al. (2009), municipalities tend to undergo a faster rate of deforestation in the initial years of settlement. Municipality-specific time trends should help to account for factors such as these.

[14] In the main equations, milk is reported in reais per litre. Prices were in the range of 0.19-0.30 reais per litre. Prices of beef range from 250 to 810 reais. 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.

[15] We opted to run our regressions using proportions rather than levels mainly due to the former being less sensitive to outliers than the latter. Regressions were, however, re-run for all land use outcomes in levels instead of proportions. Results remain very similar and are presented in Section 6 for the most stringent specification. The full set of results is available from the authors upon request.

coefficient φ and a positive sign on the coefficient δ. We expect 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. For forest cover, we expect a decline in the proportion of 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. There are, however, a number of methodological issues regarding the estimation of equation (2).

First, we adopt a fixed effects framework because it allows us to control for household fixed effects, which is likely to be important in our context to capture, for instance, (unobserved) preferences for deforestation as well as the costs of deforestation. However, it is arguably not the best way to model proportions of land cover since it has the potential to predict unfeasible values (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 estimate a generalized linear model (GLM) model with a logistic link, as suggested by Wooldridge and Papke (1996). This estimator is able to handle proportion 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, conceptually, modelling the proportions separately may not be ideal and modelling proportions in land changes using a seemingly unrelated regressions (SUR) framework could be adopted. However, Baum (2006) suggests that the asymptotic properties of SUR rely on having the number of time period larger than the number of households. However in our case, the number of households is much larger than the number of observations per household and hence, a SUR framework is not appropriate.

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 farmers in a certain municipality in a given year. In each year for each municipality, a relatively large number of farmers report the prices of beef and milk received and, as such the prices received by individual farmers are unlikely to substantially affect the prices received in a given municipality.[16] Reported prices within municipalities tend to be very consistent with those reported by our respondents. This also allows us to have a measure of prices for households who did not report the prices they received. A disadvantage of using the average of commodity prices reported at the municipal level is that it precludes the use of municipality-year fixed effects. Given that we cannot include municipality-year fixed effects, in order to capture common trends at the local scale we include municipality-specific linear time trends.

The vast majority of sampled households have resided in the same lot during the whole sample period[17] and hence, have a time-invariant measure of distance to market. Thus, a fourth issue is that

[16] Caviglia-Harris (2005) claims 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 and/or responsiveness of the household to these changes in prices.

[17] Ten households report changes in distance to market above 1 km over the sample period. Their exclusion does not affect the results.

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. While household fixed effects are necessary in order to capture other time-invariant factors that may drive outcomes such as slope and soil quality,[18] we opted to apply these only in our final two specifications, i.e. after the inclusion of our other controls. This allows us to retain distance to market in five out of seven specifications (see Section 6). Nevertheless, 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, indeed, been widely discussed in the literature, for example, in evaluating the impact of distance to school (Carneiro, 2011). However, as argued by Caviglia-Harris (2005) distance to market can be treated as exogenous since lot location and distance to market was determined by land settlement plans established by the Brazilian government.

Finally, 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. In order 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 in which we exclude these households.

6. RESULTS

Main results

Tables 2 through to 7 summarize our main results. For cattle stocking densities (Tables 2 and 3) we do not use GLM because they are not in proportions unlike land uses. The remaining tables (Tables 4-7) show the estimation results using both a GLM estimator with a log link and a fixed effects estimator. For all the tables, there are seven columns which summarize our results using an OLS and fixed effects estimators,: 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; [19] column 6 adds household fixed effects to column 5, but removes municipal trends; and, column 7 re-instates municipal trends to column 6. For Tables 4-7, there are five additional columns that present the results using the GLM estimator with a log link: column 1 shows the results when only distance to market as well as beef and milk prices are included as controls; column 2 incorporates an interaction term between prices and distance to market; column 3 adds year fixed effects; column 4 adds

[18] Land fertility closer to the extensive margin and that which might have been converted from secondary as opposed to primary forest is likely to differ. Household fixed effects should capture an unobserved effect of greater soil fertility on land more recently converted from primary forest.

[19] Note that we include lot size, measured by GIS, as one of our time-varying household controls. In our sample, about 10% of households have different lot sizes over time. Since some of these changes are large, we include this variable as a control in order to reduce the noisiness of the data. The removal of lot size makes no difference to our results.

municipality trends; column 5 adds a number of controls and their respective household averages to column 4.

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 cattle stocking density is lower yet is mostly not statistically significant, particularly in our more rigorous specifications. In columns 6 and 7 Table 2, prices of milk and beef lead to an increase in the non-dairy cattle density, significant only in the case of milk. This pattern is less pronounced in areas further away from the market, as highlighted by negative interaction terms though only significant for beef prices. Households that own dairy cattle also tend to own non-dairy cattle and it is possible that investments in one type of cattle are influenced by price changes that only affect the other type.

We note that the coefficient on milk price in column 7 Table 2, at 22.138, is quite large. It is mainly driven by the inclusion of municipal trends, which requires further explanation. First, there has been a widespread trend of decreasing cattle stocking density in the sample area, as suggested by the omitted municipal trends.[20] This implies that increases in prices may not be enough to counter the regional trend. Second, changes in real milk prices tend to be relatively small (generally in the order of 1-6 cents per litre over the sample period) and as such the effects suggested by the coefficient are large but plausible. The coefficients imply that a very large change in milk prices (five cents) increases non-dairy cattle stocking densities by a range of 0.82 to 1.08 per ha, depending on the distance to the market. In the case of dairy cattle (Table 3), we find a positive (insignificant) effect of milk prices and negative effects of beef price on dairy cattle stocking densities. These effects are more pronounced further away from the market.

TABLE 2 HERE

TABLE 3 HERE

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 specification, in OLS columns 6 and 7, we observe a (generally) statistically insignificant direct effect of beef and milk prices on the proportion of land under pasture. The coefficient for distance to market is always negative but is not always significant. Focusing on the results in OLS columns 6 and 7, the coefficient on beef prices suggests a statistically insignificant decrease in the area of pasture from a direct increase in beef prices. However, the interaction term for beef prices and distance to market suggests an increase in the proportion of land under pasture in areas far away from the market. Indeed, the coefficient on this interaction term implies a significant (at the 10% level) increase in the area under pasture for areas further away to the market relative to areas closer to the market.

The opposite pattern is found in the case of milk with the direct effect being positive, but the interaction being negative, though both coefficients are insignificant for most OLS specifications. The GLM results indicate similar results in terms of sign in the case of milk and show a significant (at the 10% level) decrease in pasture in lots further away from the market. In the case of beef prices, the GLM results are similar to the OLS results in terms an inconsistent sign of the price coefficient. Again similar to the OLS results, the coefficient of the interaction between beef prices and distance to market is consistently positive. However, it becomes statistically insignificant in GLM columns 4

[20] As can be seen in column 6, when municipal trends are excluded the coefficient of milk prices becomes three times smaller.

and 5. Overall, these results seem to highlight a differential pattern depending on the type of commodity. One possible explanation could be that since milk perishes relatively quickly in tropical environments, farmers closer to the market may be more responsive to changes in milk price than those living further away, who have to transport it over longer distances.

TABLE 4 HERE

As expected, the proportion of land under total forest cover (Table 5), which aggregates primary and secondary forest, is increasing with distance to market yet becomes statistically insignificant once municipal trends are included (column 4, both GLM and OLS). In general, the proportion of land under total forest seems to be negatively affected by commodity prices, although in OLS column 7 this relationship is positive but insignificant in the case of milk. While the coefficient for beef prices is as expected (negative), it is also not always statistically significant particularly after including household fixed effects in OLS columns 6 and 7. But conditional on distance to market, our results in these two columns suggest that higher prices of beef lead to a significantly larger loss in the proportion of 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 and a starker relationship in lots further away from the market. With respect to milk prices, the GLM estimates consistently predict a direct negative and significant effect of milk prices on total forest.

TABLE 5 HERE

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. This finding is consistent and significant for all the specifications that include distance to market. According to OLS column 1 and GLM 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. However, as we move from OLS column 2 to 7 we observe that the coefficients of prices sometimes flip sign when we include interactions, municipal trends and household fixed effects but are no longer significant. In OLS column 7, we observe that prices of milk and beef both exhibit positive but insignificant coefficients. Their respective interactions with distance to market are consistently 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 only in lots further away from market in contrast to those closer to market. Similar to the OLS results, the GLM results also suggest inconsistent results with respect to the direct effect of beef and milk prices on the proportion of land under primary forest yet a consistently negative interaction between prices and distance to market. However, the latter are no longer significant in GLM columns 4 and 5.

TABLE 6 HERE

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 significantly negative impact on the proportion of land under secondary forest. In our most stringent

specification (OLS column 7) the results suggest that both milk and beef prices negatively affect the proportion of forest cover, although this effect is only significant and is much larger in the case of beef. In terms of the interactions, increasing milk prices lead to a smaller loss of secondary forest in lots further away from the market than those closer to the market. The opposite pattern holds in the case of beef, but is insignificant. The GLM results show similar patterns both in terms of sign and significance. The main difference in the two sets of results is that in the most stringent specification, the coefficient for milk prices remains highly significant (at the 1% level). 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 further away from the market and the opposite pattern holding for milk prices. As previously noted for pasture (Table 4), one explanation could be the perishable nature of milk with farmers closer to market potentially being more responsive to changes in the price of milk than those located further away.

TABLE 7 HERE

In sum, we find limited support for the von Thünen hypothesis. Directions of effect for the coefficients of distance to market, prices and interaction terms are mostly similar for the two measures of cattle stocking density. The results for non-dairy (beef) cattle are arguably more consistent and robust than those for dairy cattle. Milk prices appear to have a positive effect on the stocking densities of both dairy and non-dairy cattle. Beef prices also seem to positively affect stocking densities of non-dairy cattle, although this effect is significantly less pronounced in lots located further away from market. As shown in Table 8, a one cent increase in milk prices is associated with a significant increase in stocking density of non-dairy cattle of 0.2 heads of cattle per hectare close to market falling to 0.16 heads further away from market. The same increase in milk prices has a much lower and statistically insignificant effect on dairy cattle, estimated at 0.0147-0.0018 heads of cattle depending on distance to market. The marginal effects of beef prices are insignificant throughout.

TABLE 8 HERE

Although the results on pasture are, for the most part, statistically insignificant, the point estimates suggest different tends depending on commodity prices. Higher milk prices are associated with larger increases in the area under pasture in areas close to the market whereas beef prices seem to be associated with a decline in the proportion of area under pasture in our fixed effects specification. Yet, this decline is significantly less pronounced the further away the lot is from the market and, beyond a certain distance, the predicted effect is positive. Specifically, as can be seen in Table 8, a 10 reais (0.01) increase in beef prices leads to a statistically insignificant decrease in pasture area of 0.3 percentage points 6km away from the market.[21] This effect gradually becomes positive in areas further away from the market and for households 80 km away from the market the same increase in beef prices leads to a 0.5 percentage points increase in area under pasture. The magnitudes estimated using GLM are a lot larger and are significant. A 10 reais increase in the real price of beef is associated with increases in pasture area: from a 0.52 percentage point increase just 6km from the market to a 1.36 percentage point increase about 80km from the market. Effects of milk prices are quite similar across specifications but are all insignificant.

Rising prices are associated with a decline in the proportion of land under total forest. Both sets of estimates suggest that prices increases, in particular 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. With

[21] All other variables other than distance to market are set at their means.

respect to the prices of milk, however, the results are more mixed. Our results for total forest are driven by the type of forest considered, which may obscure deeper patterns of land use change. More primary yet less secondary forest is found in lots further away from market. While the results for the direct effects of beef and milk prices on primary forest are largely insignificant, increases in both are associated with a significant decline in primary forest in lots further away from market. By contrast, milk prices are associated with significantly smaller losses of secondary forest in lots further away from the market, and beef prices are associated with a large and significant negative effect on secondary forest regardless of distance to market.

As can be seen in Table 9, the price of beef rather than milk seems to have a larger, more negative marginal impact on forest cover, particularly on secondary forest. A 10 reais increase in the real price of beef (0.1) leads to an estimated reduction of 0.9 (GLM estimate) to 1 (OLS) percentage point in secondary forest cover in lots found 6km from the market, rising to a reduction of 1.53 (OLS) or 1.95 (GLM) percentage points in lots located 80km from the market. While milk prices are associated with an insignificant increase in secondary forest cover in our OLS estimates, our GLM estimates indicate that a 1 cent (0.01) increase in real milk price leads to a reduction in secondary forest of between 1.5 and 2.2 percentage points depending on distance to market. Estimates of the effects of prices on total forest cover closely mirror those of secondary forest. Both sets of estimates predict significant declines in total forest cover ranging from 0.6-1.8 (OLS) or 0.8-2.3 (GLM) percentage points, with the size of this decline increasing as we move further away from the market. The estimated marginal effects for primary forest are largely insignificant.

TABLE 9 HERE

Beef and milk are produced in different ways, which may help explain some of 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). Extensification and systems focused on beef production may mostly explain the expansion of pasture area and decline of secondary forest. One reason why deforestation is more pronounced for secondary forest may be related to the differences in the cost of deforestation. Conversion of secondary forest is likely to be cheaper than converting primary forest, particularly if the former was previously left fallow. Fujisaka et al. (1996), for example, 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.

Although the marginal effects shown in Table 9 are insignificant throughout, the declines in primary forest are much larger in lots further away from market. Indeed, some of the marginal effects from the OLS estimates are positive closer to the market, which hints at a `sparing' effect. This possible 'sparing' of primary forest closer to market, however, would need to be assessed alongside the effects on secondary forest, where higher beef prices lead to lower secondary forest cover. Considering both primary and secondary forest together, there is some evidence of lower rates of deforestation in lots closer to market than in those further away. Yet, we can see from examining the two forest types separately that secondary forest bears the brunt of deforestation occurring in lots closer to market.

Another possible 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. While we might expect this requirement to be more binding closer to market due to the potential for better monitoring and hence, greater compliance, less than 1% of our households appeared to comply with the Code over the sample period.

Finally, since more secondary and less primary forest is found closer to market an 'endowment effect' might help explain why results of primary and secondary forest differ. We examine whether the initial endowment of forest plays a role in determining patterns of land use change, 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 A1 and A2 in the Appendix. For each land-use variable we performed four robustness checks using, whenever possible, 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; the `lagged 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 the robustness checks on pasture, presented in Table A1 (in the Appendix), the signs are the same in the first three columns of the robustness checks for all of the coefficients. In some cases (e.g. 'logs') the results are stronger than our main results. One difference between our robustness checks and our main specification is that milk prices seem to have a more significant impact in driving increases in pasture area than beef prices. Robustness checks on cattle stocking of non-dairy cattle reveal similar results in terms of the sign of the direct effects of both commodities. Milk price becomes insignificant despite the coefficient remaining very high and the interaction becoming positive. The robustness checks for dairy cattle, however, are similar in the sense that, as in our main results, none of the price variables is significant.

Broadly speaking, the robustness checks for the primary forest variable (Table A2) remain similar in terms of the sign of the prices of milk in all of the specifications. However, in the case of beef, while the signs remain the same in the 'No 2005' and 'Levels' specifications, they switch signs in the 'logs' and 'lagged prices' sepcifications. All the coefficients on beef prices are insignificant. The results for secondary forest, in particular, remain very similar in terms of the sign of the estimated coefficients for milk prices. In some cases (e.g. 'logs') the results of the robustness checks are even stronger than our main results. For the price of beef the same sign of the direct effect and the interaction term remains similar in three out of four robustness checks. The main exception is the 'logs' specification, where the coefficient on the direct effect switches sign (but is insignificant) and the interaction effect is very large. For total forest, the robustness checks also highlight insignificant coefficients for the parameters associated with milk prices. The significance of the interaction term between distance to market and beef price disappears and the same sign as our main estimates is only maintained in the 'No 2005' and 'levels' specifications.

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 likely to affect the household production decision. With abundant forest remaining, households may be more likely to extensify rather than intensify. Given that few households in our sample maintain 80% of their

land under forest as required under the Forest Code, we 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. We therefore split the sample into above- (`high' ) and below-median (`low') initial total forest according to this less onerous 20% requirement.[22] Since approximately half of our sample has proportions of forest below 20%, our chosen threshold of 21.6% does not differ much from the 20% threshold. Based on this sample split, we then test for differences in patterns of land use. Tables 10 and 11 show the results. For each dependent variable we use the most rigorous specification from Tables 2-7, in OLS column 7. In the Appendix (Tables A3—A8), we show a more detailed version of these results which include the specifications used in columns 4, 6 and 7 in Tables 2-7.

TABLE 10 HERE

TABLE 11 HERE

As can be seen in Table 10, the increases in land allocated to pasture also occurred mostly in lots with high initial levels of forest. As shown in Table 12, increases in prices have an insignificant (but often negative) effects on pasture lots with low initial forest cover. However, in lots with high initial forest cover far away from the market, there are large increases in pasture area associated with increases in the price of beef. Specifically, a 10 reais increase is associated with a statistically significant increase of 1.2-1.5 percentage points in pasture area.

TABLE 12 HERE

From Tables 11, we can see a clear pattern emerging., namely that more deforestation occurs in lots with initially greater proportions of land under forest, as can be seen from the coefficients for beef price and milk price comparing them across households in the `high' and `low' initial forest categories, with this holding especially true in the case of secondary forests. Table 13 shows the estimated marginal effects and these are often more than twice as large for those lots with high initial forest cover. Specifically, while a 10 reais increase in the real beef price is associated with statistically significant declines in secondary forest of 0.06-0.9 percentage points for lots with low initial forest, the same price increase is associated with a statistically significant declines of 1.59-2.22 percentage points for lots with high initial forest. Similar to the marginal effects shown in Table 9, greater declines in secondary forest are found in lots further away from market.

TABLE 13 HERE

7. DISCUSSION

Brazil has a long history of tropical deforestation, although recent trends suggest that the rate of deforestation is slowing down. Nepstad et al. (2014) argue that for Brazil to build upon its success and end 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.

[22] Initial forest cover is the forest cover in 2000 or the first year for which we have data on the household. `High' and `Low' are defined as farmers with above- and below-median proportion of forest cover. In our sample the median forest cover for the first year of observation is 21.6%.

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 more consistent and significant effects in terms of driving land-use change in Rondônia than on cattle stocking densities. The latter may, however, be compromised by the possibility that households underreport the number of cattle, perhaps for reasons of tax avoidance.

Consistent with the land rent framework we find limited 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 the market. Interestingly, land use patterns differ depending on whether we consider primary or secondary forest, and milk or beef prices. In lots further from market, primary forest is more abundant than secondary forest. There is strong evidence for the conversion of secondary forest in lots close to market driven by rising prices, and limited evidence for the intensification of non-dairy cattle production and the 'sparing' of remaining primary forest in the same lots. Yet, the ambiguous effect of prices on primary forest close to market should be viewed in light of continued conversion of secondary forest in lots near to market, as well as evidence for an 'endowment effect'.

Given how few households comply with the Forest Code, future research could be undertaken on the relative costs of primary and secondary forest conversion as well as estimating forest rents and comparing these with agricultural rents at different distances from market. Estimates of these rents could allow for an analysis of the so-called 'forest scarcity' path of economic development (Rudel et al., 2005) at the micro-scale. That said, the intensification of cattle production in lots close to market does appear to occur side by side with deforestation and extensification. Further away from market, land uses are unambiguously dominated by deforestation and extensification.

We highlight an interesting aspect of our results, which may have implications for targeting in public policy. Traditionally, policy-makers have tended to focus on reducing deforestation in areas that already have relatively little forest. However, our results suggest an `endowment effect' whereby households in plots with 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 the focus of policy-makers aiming to intensify cattle production should be geared towards households still owning proportionally large areas of forest.

Our results may be useful for policy-makers keen to incentivise and nudge households into more sustainable patterns of cattle ranching in the Amazon. Although land closer to urban agglomerations tends to be more expensive than land further away, one policy implication is simply to allocate land to landless households closer to market than further out, towards the agricultural frontier. Given the rise of hundreds if not thousands of small towns in parts of the Brazilian Amazon that once formed part of the agricultural frontier, there is a surfeit of agricultural-forest mosaiclands. While such lands would command a higher price in contrast to frontier areas a policy to assign landless households to these rather than to lots at the frontier might provide opportunities to prevent the 'legal deforestation' that would occur in the latter, more forest-rich lots.

Preventing legal deforestation on private lots could achieved by positive incentives created through a market for Environmental Reserve Quotas (*cotas de reserve ambiental*; CRA), which is presently under consideration by Brazilian federal and state governments (Soares-Filho et al., 2013). 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 in the future. Our results could be used to establish baselines for forest trends and as a means of monitoring compliance with the revised forest code over time and space. One issue that would need to be examined more closely is the need to differentiate between primary and secondary forest and provide for the means to prevent further deforestation, particularly in lots closer to the extensive margin, which tend to be located further away from the market.

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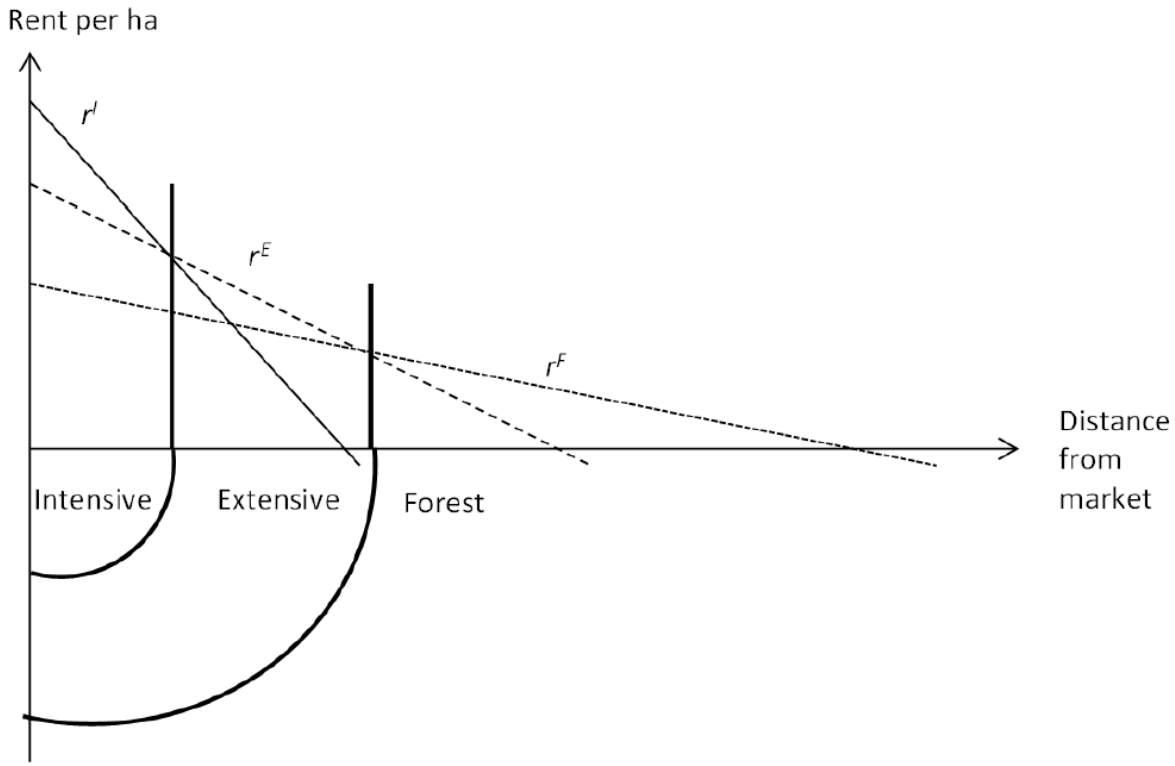
9. FIGURES AND TABLES

Table 1: Summary Statistics of observations in the sample

Variables	N	Mean	S.D	Min	Max
Household composition. Number of:					
Household members	744	6.08	4.38	0.00	36.00
Adult males (age above 10)	744	2.63	1.87	0.00	13.00
Adult females (age above 10)	744	2.34	1.76	0.00	12.00
Male children (age below 10)	744	0.61	1.06	0.00	11.00
Female children (age below 10)	744	0.51	0.95	0.00	10.00
Other household Characterisitics					
Age of household heads (average), years	742	48.48	13.48	18.00	81.00
Education of household heads (average), years	740	3.24	2.31	0.00	13.00
Income sources: Income (2000 reais)					
Off-farm labor	627	2191.47	4837.83	0.00	50000.00
Perennial crops	744	2896.34	26346.92	0.00	665082.90
Annual crops	744	284.71	1473.78	0.00	19808.15
Beef sales	744	3444.23	12454.41	0.00	193370.20
Milk	744	4562.44	6454.78	0.00	58828.59
Social security (pensions)	744	1777.24	2403.37	0.00	12520.69
Bolsa familia program (family grants)	744	57.62	210.78	0.00	2334.48
Bolsa escola program (school grants)	744	6.48	55.07	0.00	713.09
Honey and fish	744	69.10	426.90	0.00	7348.07
Other livestock	744	1041.54	2310.18	0.00	20635.36
Land uses					
Lot size (GIS, ha)	744	71.94	48.10	0.00	580.27
Agriculture area (ha) (reported)	744	4.37	6.49	0.00	76.19
Proportion of lot under agriculture (reported)	723	0.11	0.16	0.00	1.67
Pasture area (ha) (GIS)	744	52.52	38.74	0.00	483.34
Proportion of lot under pasture (GIS)	736	0.73	0.21	0.04	1.00
Primary forest (ha) (GIS)	744	11.28	14.21	0.00	133.70
Primary forest as a proportion of lot size (GIS)	736	0.15	0.15	0.00	0.92
Secondary forest (ha) (GIS)	744	5.18	7.02	0.00	66.83
Secondary forest as a proportion of lot size (GIS)	736	0.08	0.09	0.00	0.64
Total forest cover (ha) (GIS)	744	16.46	18.15	0.00	200.53
Total forest cover as a proportion of lot size (GIS)	736	0.23	0.19	0.00	0.94
Cattle stocking density					
Non-dairy cattle per ha (net of forest)	733	1.34	1.37	0.00	15.98
Dairy cattle per ha (net of forest)	736	0.38	0.42	0.00	3.87
Market variables					
Beef price (real prices, '000 reais)	743	0.31	0.05	0.25	0.42
Milk price (real prices, reais)	743	0.24	0.03	0.18	0.28
Distance to the centre of Ouro Preto do Oeste (km)	744	39.47	18.34	5.26	82.13

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.

Figure 1: Rent and distance from market



Source: adapted from Angelsen (2007)

Figure 2: Evolution of milk and beef prices over time

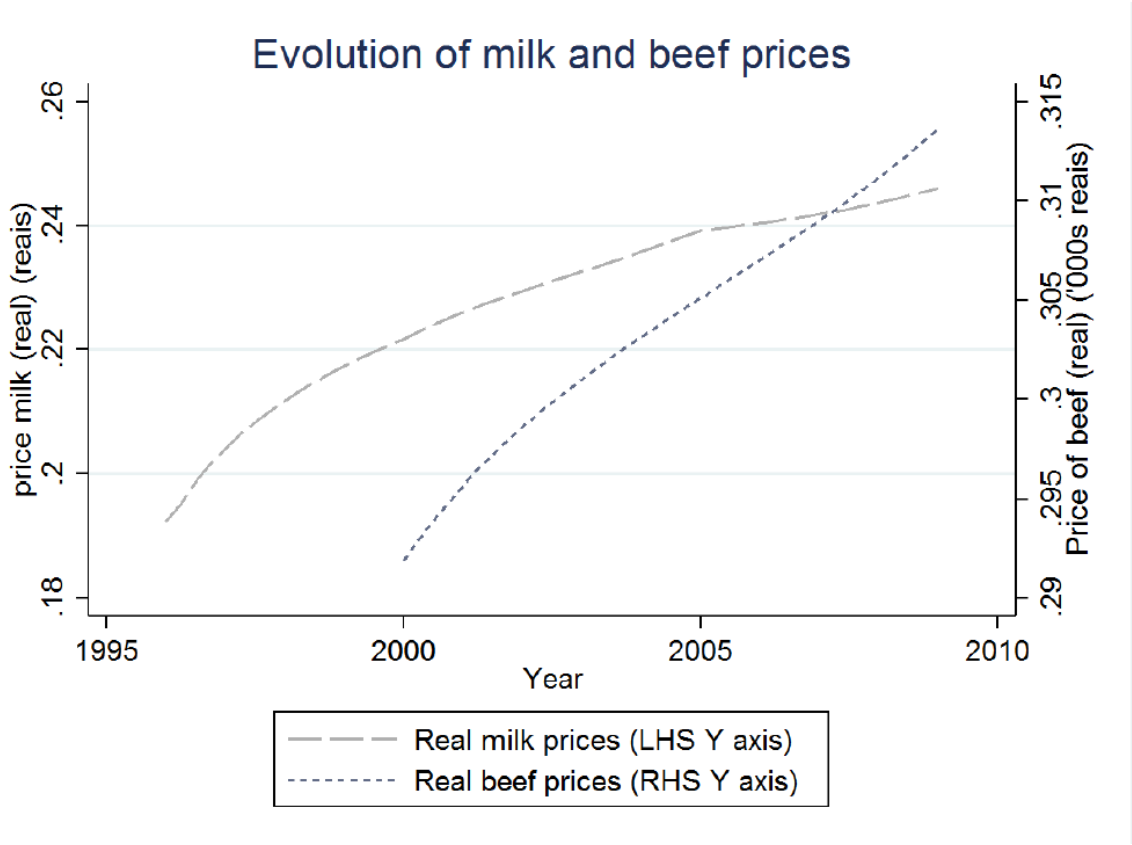


Figure 3: Proportion of land under forest cover

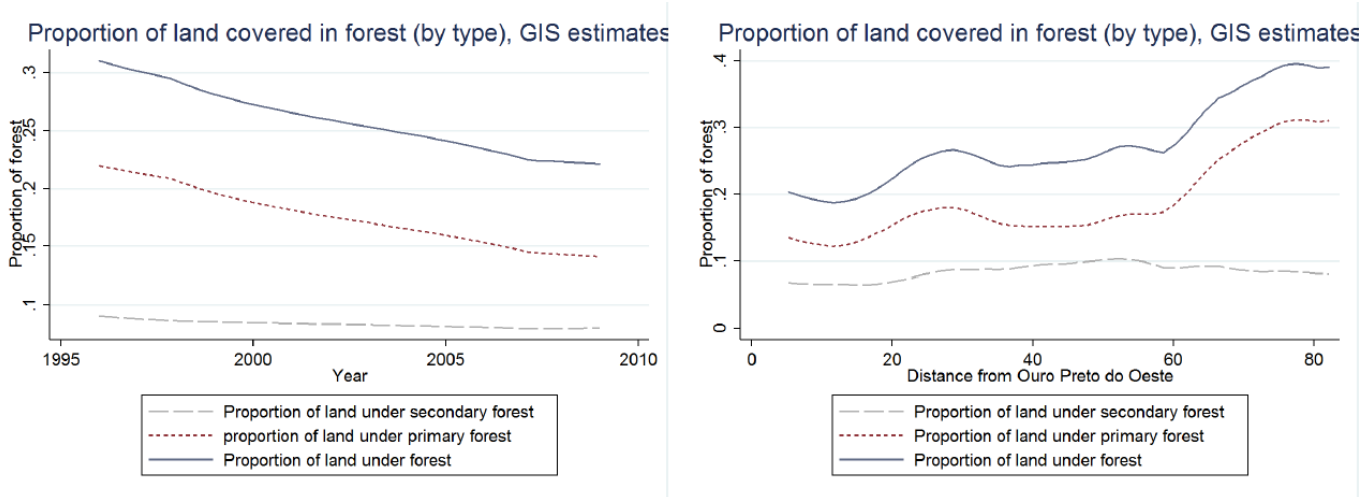


Figure 4: Proportion of land under pasture and number of cattle in the lot

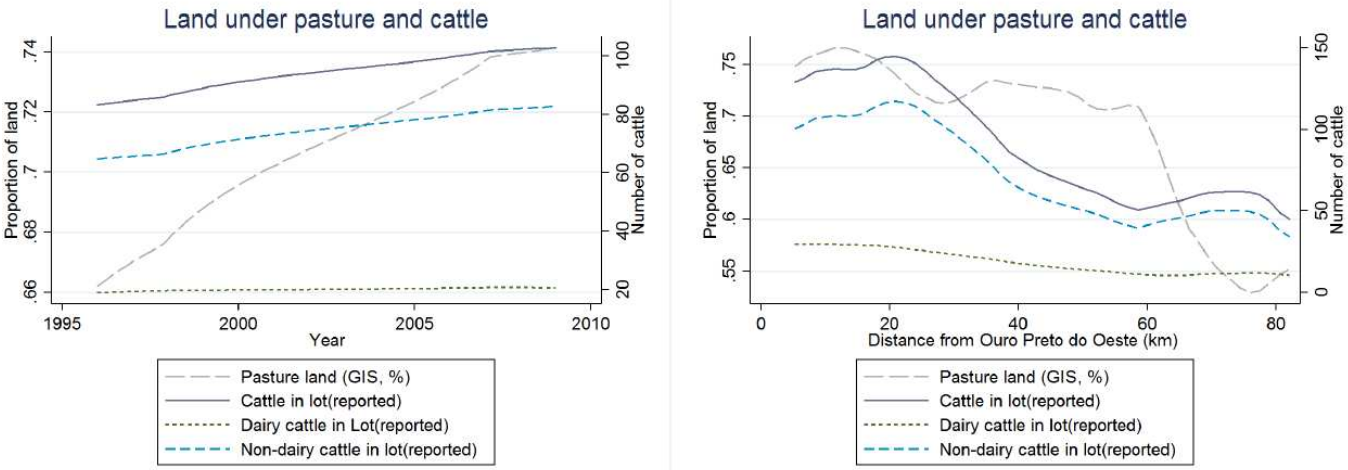


Figure 5: Cattle stocking density

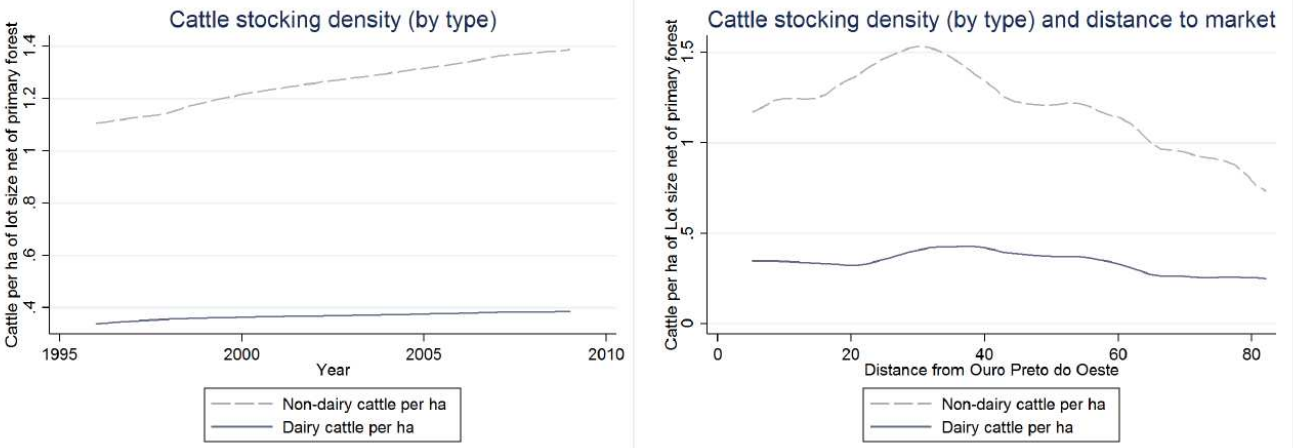


Table 2: Non-dairy cattle regression results - OLS

	OLS						
Variables	1	2	3	4	5	6	7
Dist. to Ouro Preto do Oeste (OPO) (km)	-0.006**	-0.024	-0.027	-0.029	-0.028		
	0.003	0.018	0.018	0.025	0.025		
Av. milk price in the municipio (real)	3.750***	1.852	8.024	4.811	2.859	7.167	22.138**
	1.285	2.938	6.605	7.902	8.275	7.198	11.113
Av. beef price in the municipio (real)	3.449***	2.801	2.423	-0.84	-0.442	0.426	4.378
	1.179	2.5	3.487	4.11	4.083	3.046	4.736
Av. milk price in the municipio (real) * Dist. OPO		0.05	0.054	0.071	0.072	-0.018	-0.072
		0.068	0.071	0.073	0.074	0.073	0.072
Av. Beef price in the municipio (real) * Dist. OPO		0.019	0.031	0.011	0.001	-0.041	-0.121**
		0.062	0.057	0.072	0.073	0.05	0.055
Year fixed effects	No	No	Yes	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	Yes	Yes	No	Yes
Controls	No	No	No	No	Yes	Yes	Yes
Household average of controls	No	No	No	No	No	No	No
Household fixed effects	No	No	No	No	No	Yes	Yes
Number of observations	732	732	732	732	729	729	729
Number of households	308	308	308	308	306	306	306
R-squared	0.022	0.02	0.018	0.033	0.041	0.021	0.035

Values in parentheses denote standard errors at the household level. *, ** 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, lot size (ha, GIS estimate) and household size.

Table 3: Dairy cattle regression results - OLS

	OLS						
Variables	1	2	3	4	5	6	7
Dist. to Ouro Preto do Oeste (OPO) (km)	-0.001	-0.011*	-0.013**	-0.001	-0.002		
	0.001	0.006	0.006	0.008	0.007		
Av. milk price in the municipio (real)	2.289***	0.989	4.469*	1.741	0.92	0.872	1.433
	0.43	0.975	2.672	2.882	2.978	2.448	3.185
Av. beef price in the municipio (real)	-0.836***	-1.096**	-1.742**	0.618	0.32	-0.454	-0.136
	0.231	0.475	0.757	1.02	1.037	0.784	1.284
Av. milk price in the municipio (real) * Dist. OPO		0.034	0.041*	0.01	0.013	0.011	0.007
		0.024	0.024	0.027	0.027	0.02	0.021
Av. beef price in the municipio (real) * Dist. OPO		0.008	0.011	-0.013	-0.014	0.009	-0.001
		0.011	0.013	0.016	0.016	0.014	0.019
Year fixed effects	No	No	Yes	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	Yes	Yes	No	Yes
Controls	No	No	No	No	Yes	Yes	Yes
Household average of controls	No	No	No	No	No	No	No
Household fixed effects	No	No	No	No	No	Yes	Yes
Number of observations	735	735	735	735	731	731	731
Number of households	309	309	309	309	306	306	306
R-squared	0.037	0.037	0.04	0.055	0.071	0.075	0.071

Values in parentheses denote clustered standard errors at the household level. *, ** 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, lot size (ha, GIS estimate) and household size.

Table 4: Pasture regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Dist. to Ouro Preto do Oeste (OPO) (km)	-0.012***	-0.02	-0.027	0.007	0.003	-0.002***	-0.006	-0.007*	-0.001	-0.001		
	(0.003)	(0.018)	(0.019)	(0.021)	(0.022)	(0.001)	(0.004)	(0.004)	(0.004)	(0.005)		
Av. milk price in the municipio (real)	4.382***	6.303***	14.525**	7.569	6.839	0.873***	1.017**	2.696**	1.212	1.389	0.317	1.01
	(0.998)	(2.262)	(5.885)	(5.929)	(5.539)	(0.199)	(0.424)	(1.157)	(1.175)	(1.208)	(0.930)	(1.010)
Av. beef price in the municipio (real)	1.580***	-0.774	-1.279	5.019**	3.877	0.308***	-0.191	-0.291	0.940*	0.783	-0.175	-0.424
	(0.583)	(1.286)	(1.891)	(2.502)	(2.580)	(0.109)	(0.240)	(0.356)	(0.491)	(0.500)	(0.292)	(0.451)
Av. milk price in the municipio (real) * Dist. OPO		-0.047	-0.037	-0.137**	-0.120*		-0.003	-0.002	-0.019	-0.021	-0.015	-0.012
		(0.054)	(0.055)	(0.062)	(0.062)		(0.011)	(0.011)	(0.012)	(0.013)	(0.010)	(0.010)
Av. beef price in the municipio (real) * Dist. OPO		0.063*	0.083**	0.021	0.021		0.014**	0.017**	0.006	0.008	0.011*	0.012*
		(0.035)	(0.039)	(0.046)	(0.046)		(0.007)	(0.008)	(0.009)	(0.009)	(0.006)	(0.007)
Year fixed effects	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes
Controls	No	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes
Household average of controls	No	No	No	No	Yes	No	No	No	No	No	No	No
Household fixed effects	No	No	No	No	No	No	No	No	No	No	Yes	Yes
Number of observations	735	735	735	735	731	735	735	735	735	731	731	731
Number of households	309	309	309	309	309	309	309	309	309	306	306	306
R-squared						0.061	0.062	0.062	0.116	0.135	0.088	0.088

Values in parentheses denote clustered standard errors at the household level. *, ** 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, lot size (ha, GIS estimate) and household size.

Table 5: Total forest regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Dist. to Ouro Preto do Oeste (OPO) (km)	0.011***	0.043**	0.049**	0.011	0.017	0.002***	0.010***	0.011***	0.005	0.005		
	(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)	-4.465***	-2.613	-9.703*	-10.381*	-9.904*	-0.815***	-0.264	-1.476	-1.422	-1.695	-0.166	0.752
	(1.077)	(2.266)	(5.608)	(6.037)	(5.626)	(0.200)	(0.397)	(0.981)	(1.104)	(1.143)	(0.690)	(0.724)
Av. beef price in the municipio (real)	-2.453***	0.229	0.159	-8.632***	-7.631***	-0.424***	0.138	0.114	-1.451***	-1.311***	-0.190	-0.523
	(0.613)	(1.358)	(1.968)	(2.668)	(2.657)	(0.103)	(0.225)	(0.328)	(0.464)	(0.471)	(0.258)	(0.403)
Av. milk price in the municipio (real) * Dist. OPO		-0.047	-0.048	0.064	0.047		-0.015	-0.015	0.002	0.004	-0.007	-0.003
		(0.052)	(0.056)	(0.063)	(0.063)		(0.010)	(0.010)	(0.011)	(0.012)	(0.007)	(0.008)
Av. beef price in the municipio (real) * Dist. OPO		-0.072**	-0.093**	-0.022	-0.029		-0.016**	-0.019***	-0.008	-0.01	-0.019***	-0.016**
		(0.036)	(0.040)	(0.047)	(0.048)		(0.007)	(0.007)	(0.008)	(0.009)	(0.005)	(0.007)
Year fixed effects	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes
Controls	No	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes
Household average of controls	No	No	No	No	Yes	No	No	No	No	No	No	No
Household fixed effects	No	No	No	No	No	No	No	No	No	No	Yes	Yes
Number of observations	735	735	735	735	731	735	735	735	735	731	731	731
Number of households	309	309	309	309	309	309	309	309	309	306	306	306
R-squared						0.053	0.056	0.056	0.11	0.132	0.193	0.198

Values in parentheses denote clustered standard errors at the household level. *, ** 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, lot size (ha, GIS estimate) and household size.

Table 6: Primary forest regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Dist. to Ouro Preto do Oeste (OPO) (km)	0.011***	0.073***	0.085***	0.038*	0.044**	0.001***	0.013***	0.014***	0.009***	0.009***		
	(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)	-3.874***	1.262	-8.169	0.71	2.367	-0.523***	0.404	-0.635	0.154	0.176	0.969	0.79
	(1.144)	(2.585)	(6.296)	(7.028)	(6.263)	(0.162)	(0.325)	(0.783)	(0.977)	(1.004)	(0.589)	(0.781)
Av. beef price in the municipio (real)	-4.834***	-0.401	1.402	-3.479	-1.812	-0.569***	0.16	0.344	-0.414	-0.258	0.649***	0.524
	(0.695)	(1.391)	(2.171)	(2.807)	(2.781)	(0.079)	(0.159)	(0.250)	(0.362)	(0.366)	(0.230)	(0.350)
Av. milk price in the municipio (real) * Dist. OPO		-0.125**	-0.155**	-0.058	-0.075		-0.025***	-0.027***	-0.015	-0.014	-0.019***	-0.017**
		(0.058)	(0.063)	(0.065)	(0.065)		(0.009)	(0.009)	(0.009)	(0.009)	(0.006)	(0.007)
Av. beef price in the municipio (real) * Dist. OPO		-0.114***	-0.132***	-0.01	-0.014		-0.021***	-0.022***	-0.008	-0.009	-0.015***	-0.010*
		(0.036)	(0.042)	(0.048)	(0.047)		(0.005)	(0.005)	(0.007)	(0.006)	(0.004)	(0.005)
Year fixed effects	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes
Controls	No	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes
Household average of controls	No	No	No	No	Yes	No	No	No	No	No	No	No
Household fixed effects	No	No	No	No	No	No	No	No	No	No	Yes	Yes
Number of observations	735	735	735	735	731	735	735	735	735	731	731	731
Number of households	309	309	309	309	309	309	309	309	309	306	306	306
R-squared						0.067	0.083	0.084	0.123	0.144	0.254	0.257

Values in parentheses denote clustered standard errors at the household level. *, ** 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, lot size (ha, GIS estimate) and household size.

Table 7: Secondary forest regression results - GLM and OLS

	GLM					OLS						
Variables	1	2	3	4	5	1	2	3	4	5	6	7
Dist. to Ouro Preto do Oeste (OPO) (km)	0.006**	-0.045*	-0.046*	-0.057**	-0.054**	0.000**	-0.003*	-0.003*	-0.003	-0.004*		
	(0.003)	(0.025)	(0.024)	(0.026)	(0.027)	(0.000)	(0.002)	(0.002)	(0.002)	(0.002)		
Av. milk price in the municipio (real)	-4.137**	-10.437***	-12.456*	-43.217***	-46.197***	-0.292**	-0.668***	-0.841*	-1.576***	-1.871***	-1.134**	-0.038
	(1.696)	(3.459)	(6.548)	(8.946)	(8.708)	(0.119)	(0.246)	(0.472)	(0.566)	(0.591)	(0.517)	(0.742)
Av. beef price in the municipio (real)	2.065***	0.372	-2.416	-17.021***	-17.835***	0.145***	-0.022	-0.231	-1.037***	-1.053***	-0.840***	-1.047***
	(0.731)	(1.685)	(2.199)	(3.612)	(3.628)	(0.056)	(0.122)	(0.166)	(0.238)	(0.242)	(0.181)	(0.298)
Av. milk price in the municipio (real) * Dist. OPO		0.162**	0.205**	0.356***	0.350***		0.010*	0.012**	0.017***	0.018***	0.012**	0.014**
		(0.081)	(0.082)	(0.097)	(0.101)		(0.006)	(0.006)	(0.006)	(0.006)	(0.005)	(0.006)
Av. beef price in the municipio (real) * Dist. OPO		0.048	0.017	-0.054	-0.064		0.005	0.003	0	0	-0.004	-0.006
		(0.043)	(0.045)	(0.060)	(0.060)		(0.003)	(0.004)	(0.004)	(0.004)	(0.003)	(0.004)
Year fixed effects	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	Yes	Yes	No	No	No	Yes	Yes	No	Yes
Controls	No	No	No	No	Yes	No	No	No	No	Yes	Yes	Yes
Household average of controls	No	No	No	No	Yes	No	No	No	No	No	No	No
Household fixed effects	No	No	No	No	No	No	No	No	No	No	Yes	Yes
Number of observations	735	735	735	735	731	735	735	735	735	731	731	731
Number of households	309	309	309	309	309	309	309	309	309	306	306	306
R-squared						0.02	0.021	0.025	0.114	0.148	0.123	0.136

Values in parentheses denote clustered standard errors at the household level. *, ** 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, lot size (ha, GIS estimate) and household size.

Table 8: 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	0.797	0.936	1.475	21.695**
10	13.168	0.751	0.852	1.524	21.192**
25	27.144	0.601	0.683	1.620	20.188*
50	38.572	0.419	0.548	1.697	19.385*
Mean	39.435	0.398	0.535	1.704	19.305*
75	50.880	0.150	0.397	1.783	18.484*
90	66.680	-0.275	0.207	1.892	17.350*
99	79.760	-0.674	0.049	1.982	16.410
		Beef prices			
1	6.165	0.524*	-0.349	-0.145	3.634
10	13.168	0.594**	-0.264	-0.155	2.789
25	27.144	0.750**	-0.094	-0.175	1.101
50	38.572	0.885**	0.042	-0.191	-0.249
Mean	39.435	0.898***	0.055	-0.193	-0.385
75	50.880	1.041***	0.194	-0.210	-1.764
90	66.680	1.230**	0.386	-0.233	-3.672
99	79.760	1.365**	0.545	-0.252	-5.251

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

Table 9: 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	0.125	0.686	-2.208***	0.045	-1.079*	0.732
10	13.168	0.103	0.568	-2.197***	0.141	-1.148*	0.709
25	27.144	0.032	0.333	-2.150***	0.331	-1.276	0.663
50	38.572	-0.059	0.144	-2.084***	0.483	-1.363	0.627
Mean	39.435	-0.070	0.126	-2.076***	0.498	-1.370	0.624
75	50.880	-0.205	-0.067	-1.975***	0.654	-1.433	0.586
90	66.680	-0.461	-0.333	-1.778***	0.868	-1.466	0.535
99	79.760	-0.730	-0.554	-1.556**	1.046	-1.437	0.493
				Beef prices			
1	6.165	-0.124	0.462	-0.914***	-1.085***	-0.877***	-0.623*
10	13.168	-0.149	0.390	-0.987***	-1.128***	-0.992***	-0.737**
25	27.144	-0.209	0.248	-1.146***	-1.213***	-1.248***	-0.965***
50	38.572	-0.271	0.134	-1.289***	-1.281***	-1.476***	-1.147***
Mean	39.435	-0.277	0.123	-1.304***	-1.288***	-1.499***	-1.165***
75	50.880	-0.353	0.006	-1.467***	-1.357***	-1.745***	-1.352***
90	66.680	-0.474	-0.155	-1.718***	-1.454***	-2.084***	-1.609***
99	79.760	-0.584	-0.288	-1.951***	-1.534***	-2.340***	-1.822***

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

Table 10: Further results - Pasture and cattle stocking density by initial forest cover

	Pasture		Dairy cattle		Non-dairy cattle	
Variables	High	Low	High	Low	High	Low
Av. milk price in the municipio (real)	2.124	-0.668	1.633	0.7	9.192	37.376*
	(1.490)	(1.164)	(4.072)	(5.592)	(10.437)	(22.074)
Av. beef price in the municipio (real)	-0.65	0.424	0.836	-1.298	7.494	0.77
	(0.612)	(0.423)	(1.413)	(2.571)	(5.980)	(8.207)
Av. milk price in the municipio (real) * Dist. OPO	-0.030***	-0.007	0.023	-0.006	0.01	-0.206
	(0.011)	(0.013)	(0.023)	(0.038)	(0.089)	(0.157)
Av. Beef price in the municipio (real) * Dist. OPO	0.027***	-0.012	-0.034	0.029	-0.182**	-0.074
	(0.009)	(0.009)	(0.025)	(0.035)	(0.088)	(0.084)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Municipality trends	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	372	359	372	359	371	358
Number of households	150	160	150	160	150	160
R-squared	0.234	0.157	0.098	0.068	0.071	0.031

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table 11: Further results - Forest by initial forest cover

	Primary Forest		Secondary Forest		Total Forest	
Variables	High	Low	High	Low	High	Low
Av. milk price in the municipio (real)	1.217	0.16	-0.301	0.138	0.916	0.298
	(1.362)	(0.601)	(1.212)	(0.525)	(1.207)	(0.627)
Av. beef price in the municipio (real)	0.685	0.214	-1.529***	-0.576**	-0.844	-0.362
	(0.482)	(0.333)	(0.504)	(0.283)	(0.516)	(0.420)
Av. milk price in the municipio (real) * Distance OPO	-0.020*	-0.008	0.031***	0.004	0.012	-0.004
	(0.010)	(0.006)	(0.010)	(0.005)	(0.010)	(0.007)
Av. Beef price in the municipio (real) * Distance OPO	-0.012	-0.003	-0.009	-0.005	-0.021**	-0.008
	(0.008)	(0.005)	(0.007)	(0.005)	(0.009)	(0.007)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Municipality trends	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	372	359	372	359	372	359
Number of households	150	160	150	160	150	160
R-squared	0.382	0.22	0.216	0.093	0.328	0.131

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table 12: 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	1.899	-0.711	1.805	0.663	9.265	36.108*
10	18.265	11.968	1.578	-0.751	2.050	0.629	9.378	34.945*
25	29.209	24.787	1.251	-0.824	2.299	0.568	9.478	32.816
50	42.325	36.525	0.860	-0.924	2.599	0.484	9.606	29.913
Mean	42.797	36.089	0.845	-0.921	2.610	0.487	9.612	29.999
75	55.836	45.420	0.456	-0.988	2.907	0.430	9.739	28.033
90	71.246	58.577	-0.004	-1.081	3.258	0.352	9.890	25.327
99	80.469	77.103	-0.280	-1.212	3.469	0.242	9.980	21.516
				Beef prices				
1	7.532	6.165	-0.450	0.350	0.577	-1.117	6.124	0.314
10	18.265	11.968	-0.165	0.283	0.207	-0.951	4.025	-0.103
25	29.209	24.787	0.126	0.159	-0.171	-0.647	2.182	-0.868
50	42.325	36.525	0.475	-0.009	-0.623	-0.232	-0.203	-1.910
Mean	42.797	36.089	0.489	-0.005	-0.640	-0.243	-0.310	-1.879
75	55.836	45.420	0.835	-0.118	-1.089	0.036	-2.660	-2.585
90	71.246	58.577	1.244*	-0.275	-1.620	0.423	-5.462	-3.557
99	80.469	77.103	1.490*	-0.496	-1.938	0.967	-7.139	-4.925

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

Table 13: 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	1.069	0.114	-0.066	0.161	1.003	0.275
10	18.265	11.968	0.859	0.071	0.269	0.182	1.128	0.254
25	29.209	24.787	0.645	-0.006	0.610	0.221	1.255	0.214
50	42.325	36.525	0.388	-0.113	1.019	0.273	1.407	0.161
Mean	42.797	36.089	0.378	-0.110	1.035	0.272	1.413	0.162
75	55.836	45.420	0.124	-0.181	1.440	0.307	1.564	0.126
90	71.246	58.577	-0.178	-0.280	1.921	0.356	1.743	0.076
99	80.469	77.103	-0.358	-0.419	2.208	0.425	1.850	0.006
				Beef prices				
1	7.532	6.165	0.595	0.197	-1.594***	-0.605**	-0.999**	-0.408
10	18.265	11.968	0.467	0.181	-1.687***	-0.632**	-1.220**	-0.451
25	29.209	24.787	0.336	0.152	-1.781***	-0.680***	-1.445***	-0.528
50	42.325	36.525	0.179	0.112	-1.894***	-0.746***	-1.715***	-0.634**
Mean	42.797	36.089	0.173	0.113	-1.898***	-0.745***	-1.725***	-0.631**
75	55.836	45.420	0.017	0.086	-2.010***	-0.789***	-1.993***	-0.703**
90	71.246	58.577	-0.167	0.049	-2.143***	-0.851***	-2.310***	-0.801**
99	80.469	77.103	-0.277	-0.003	-2.223***	-0.937***	-2.500***	-0.940**

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

Appendix

Table A1: 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)	2.633**	144.953*	2.030**	-3.946	14.196	3.6	130.554	-0.873	1.343	-6.15
	(1.207)	(83.973)	(0.832)	(3.981)	(8.661)	(2.233)	(81.675)	(3.888)	(2.242)	(9.947)
Av. milk price in the municipio (real) * Dist. OPO (km)	-0.01	-1.873*	-0.255**	0.007	0.027	0.544**	-0.13	0.006	-0.112	-0.004
	(0.011)	(1.047)	(0.104)	(0.014)	(0.076)	(0.275)	(0.161)	(0.024)	(0.351)	(0.046)
Av. beef price in the municipio (real)	-0.851	-14.652	-1.135**	0.141	1.96	0.838	10.146	-0.118	1.271	2.688
	(0.572)	(44.565)	(0.494)	(0.776)	(5.238)	(1.120)	(17.383)	(1.650)	(1.062)	(2.686)
Av. beef price in the municipio (real) * Dist. OPO (km)	0.01	0.014	0.240***	0.008	-0.105*	-0.235	0.289*	0.015	-0.188	-0.057
	(0.010)	(0.710)	(0.087)	(0.020)	(0.058)	(0.275)	(0.164)	(0.022)	(0.270)	(0.051)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	462	739	731	422	461	670	420	462	613	422
Number of households	177	310	310	295	177	304	294	177	288	295
R-squared	0.124	0.798	0.271	0.149	0.056	0.075	0.087	0.088	0.084	0.103

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.
In the SUR regression the p-value of the Breusch-Pagan test of independence of errors was rejected with a p-value of 0.000. The error correlation between primary and secondary was 0.221.
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.
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 A2: 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)	0.426	29.347	3.088	4.913**	-0.579	-21.115	-16.229***	-4.811*	-0.152	8.232	-1.17	0.102
	(0.824)	(63.787)	(1.956)	(2.157)	(0.949)	(60.219)	(3.552)	(2.456)	(0.784)	(58.471)	(1.536)	(2.673)
Av. milk price in the municipio (real) * Dist. OPO (km)	-0.019***	-0.947*	-0.553	-0.009	0.014*	0.819*	3.022***	0.003	-0.005	-0.128	0.405	-0.006
	(0.007)	(0.551)	(0.390)	(0.007)	(0.007)	(0.452)	(0.572)	(0.012)	(0.009)	(0.633)	(0.356)	(0.012)
Av. Beef price in the municipio (real)	0.463	10.746	-0.391	-0.245	-0.975***	-58.995**	2.661	-0.598	-0.512	-48.249	-1.158	-0.843
	(0.431)	(35.574)	(1.486)	(0.322)	(0.352)	(24.417)	(2.265)	(0.596)	(0.501)	(42.156)	(1.241)	(0.633)
Av. beef price in the municipio (real) * Dist. OPO (km)	-0.003	-0.098	0.315	0.009	-0.009	-0.484	-2.047***	0.009	-0.012	-0.581	0.042	0.019
	(0.007)	(0.457)	(0.386)	(0.009)	(0.006)	(0.356)	(0.517)	(0.014)	(0.009)	(0.589)	(0.300)	(0.014)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	462	739	658	422	462	739	678	422	462	739	678	422
Number of households	177	310	296	295	177	310	298	295	177	310	298	295
R-squared	0.269	0.309	0.281	0.343	0.152	0.206	0.299	0.264	0.236	0.333	0.225	0.048

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. In the SUR regression the p-value of the Breusch-Pagan test of independence of errors was rejected with a p-value of 0.000. The error correlation between primary and secondary was 0.221. The error correlation between primary forest and pasture was -0.805. The error correlation between secondary forest and pasture was -0.603.
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.
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 A3: Further results - Non-dairy cattle by initial forest cover

	High	Low	High	Low	High	Low
Variables	1	2	3	4	5	6
Dist. to Ouro Preto do Oeste (OPO) (km)	0.029	-0.070**				
	(0.024)	(0.030)				
Av. milk price in the municipio (real)	4.347	0.13	-6.382	24.732**	9.192	37.376*
	(3.675)	(5.082)	(10.771)	(10.821)	(10.437)	(22.074)
Av. beef price in the municipio (real)	9.254**	-3.432	2.601	-2.849	7.494	0.77
	(3.806)	(3.897)	(2.987)	(5.917)	(5.980)	(8.207)
Av. milk price in the municipio (real) * Dist. OPO	0.006	0.067	0.062	-0.123	0.01	-0.206
	(0.069)	(0.144)	(0.074)	(0.151)	(0.089)	(0.157)
Av. Beef price in the municipio (real) * Dist. OPO	-0.132**	0.183	-0.148**	0.061	-0.182**	-0.074
	(0.063)	(0.122)	(0.071)	(0.094)	(0.088)	(0.084)
Year fixed effects	No	No	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	No	Yes	Yes
Controls	No	No	Yes	Yes	Yes	Yes
Household fixed effects	No	No	Yes	Yes	Yes	Yes
Number of observations	372	360	371	358	371	358
Number of households	150	160	150	160	150	160
R-squared	0.047	0.003	0.036	0.015	0.071	0.031

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table A4: Further results - Dairy cattle by initial forest cover

	High	Low	High	Low	High	Low
Variables	1	2	3	4	5	6
Dist. to Ouro Preto do Oeste (OPO) (km)	-0.012	-0.005				
	(0.007)	(0.011)				
Av. milk price in the municipio (real)	0.268	2.061	-1.93	3.907	1.633	0.7
	(1.301)	(1.565)	(3.111)	(4.424)	(4.072)	(5.592)
Av. beef price in the municipio (real)	-0.803	-1.429**	-0.01	-1.075	0.836	-1.298
	(0.756)	(0.602)	(0.961)	(1.270)	(1.413)	(2.571)
Av. milk price in the municipio (real) * Dist. OPO	0.049*	0.003	0.031	-0.006	0.023	-0.006
	(0.027)	(0.045)	(0.021)	(0.041)	(0.023)	(0.038)
Av. Beef price in the municipio (real) * Dist. OPO	-0.005	0.02	-0.02	0.039	-0.034	0.029
	(0.017)	(0.016)	(0.020)	(0.024)	(0.025)	(0.035)
Year fixed effects	No	No	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	No	Yes	Yes
Controls	No	No	Yes	Yes	Yes	Yes
Household fixed effects	No	No	Yes	Yes	Yes	Yes
Number of observations	373	362	372	359	372	359
Number of households	150	160	150	160	150	160
R-squared	0.041	0.032	0.099	0.061	0.098	0.068

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table A5: Further results - Pasture by initial forest cover

	High	Low	High	Low	High	Low
Variables	1	2	3	4	5	6
Dist. to Ouro Preto do Oeste (OPO) (km)	-0.002	0.002				
	(0.004)	(0.003)				
Av. milk price in the municipio (real)	2.081***	0.194	2.753**	-2.462**	2.124	-0.668
	(0.550)	(0.334)	(1.233)	(1.014)	(1.490)	(1.164)
Av. beef price in the municipio (real)	-0.454	0.346	-0.34	0.424	-0.65	0.424
	(0.339)	(0.244)	(0.450)	(0.284)	(0.612)	(0.423)
Av. milk price in the municipio (real) * Dist. OPO	-0.028**	0.004	-0.032***	-0.007	-0.030***	-0.007
	(0.014)	(0.009)	(0.012)	(0.012)	(0.011)	(0.013)
Av. Beef price in the municipio (real) * Dist. OPO	0.024***	-0.012*	0.025***	-0.015**	0.027***	-0.012
	(0.009)	(0.007)	(0.008)	(0.006)	(0.009)	(0.009)
Year fixed effects	No	No	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	No	Yes	Yes
Controls	No	No	Yes	Yes	Yes	Yes
Household fixed effects	No	No	Yes	Yes	Yes	Yes
Number of observations	373	362	372	359	372	359
Number of households	150	160	150	160	150	160
R-squared	0.06	0.01	0.232	0.135	0.234	0.157

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table A6: Further results - Total forest by initial forest cover

	High	Low	High	Low	High	Low
Variables	1	2	3	4	5	6
Dist. to Ouro Preto do Oeste (OPO) (km)	0.007*	0.002				
	(0.004)	(0.002)				
Av. milk price in the municipio (real)	-0.922*	0.079	-1.351	0.74	0.916	0.298
	(0.499)	(0.262)	(0.984)	(0.743)	(1.207)	(0.627)
Av. beef price in the municipio (real)	0.165	-0.092	-0.32	-0.253	-0.844	-0.362
	(0.331)	(0.152)	(0.394)	(0.221)	(0.516)	(0.420)
Av. milk price in the municipio (real) * Dist. OPO	-0.003	-0.005	0.004	-0.004	0.012	-0.004
	(0.012)	(0.007)	(0.010)	(0.006)	(0.010)	(0.007)
Av. Beef price in the municipio (real) * Dist. OPO	-0.018**	-0.001	-0.023***	-0.006	-0.021**	-0.008
	(0.009)	(0.004)	(0.007)	(0.005)	(0.009)	(0.007)
Year fixed effects	No	No	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	No	Yes	Yes
Controls	No	No	Yes	Yes	Yes	Yes
Household fixed effects	No	No	Yes	Yes	Yes	Yes
Number of observations	373	362	372	359	372	359
Number of households	150	160	150	160	150	160
R-squared	0.045	-0.003	0.315	0.123	0.328	0.131

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table A7: Further results - Primary forest by initial forest cover

	High	Low	High	Low	High	Low
Variables	1	2	3	4	5	6
Dist. to Ouro Preto do Oeste (OPO) (km)	0.013***	0.004*				
	(0.004)	(0.002)				
Av. milk price in the municipio (real)	0.26	0.291	0.959	0.990*	1.217	0.16
	(0.513)	(0.210)	(0.865)	(0.530)	(1.362)	(0.601)
Av. beef price in the municipio (real)	0.125	-0.052	1.028***	0.095	0.685	0.214
	(0.251)	(0.103)	(0.384)	(0.159)	(0.482)	(0.333)
Av. milk price in the municipio (real) * Dist. OPO	-0.023**	-0.009	-0.025**	-0.006	-0.020*	-0.008
	(0.011)	(0.006)	(0.011)	(0.005)	(0.010)	(0.006)
Av. Beef price in the municipio (real) * Dist. OPO	-0.023***	-0.005*	-0.019***	0	-0.012	-0.003
	(0.007)	(0.003)	(0.006)	(0.003)	(0.008)	(0.005)
Year fixed effects	No	No	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	No	Yes	Yes
Controls	No	No	Yes	Yes	Yes	Yes
Household fixed effects	No	No	Yes	Yes	Yes	Yes
Number of observations	373	362	372	359	372	359
Number of households	150	160	150	160	150	160
R-squared	0.087	0.032	0.375	0.198	0.382	0.22

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.

Table A8: Further results - Secondary forest by initial forest cover

	High	Low	High	Low	High	Low
Variables	1	2	3	4	5	6
Dist. to Ouro Preto do Oeste (OPO) (km)	-0.006**	-0.002				
	(0.003)	(0.002)				
Av. milk price in the municipio (real)	-1.182***	-0.212	-2.310***	-0.25	-0.301	0.138
	(0.424)	(0.155)	(0.784)	(0.460)	(1.212)	(0.525)
Av. beef price in the municipio (real)	0.04	-0.04	-1.347***	-0.347**	-1.529***	-0.576**
	(0.194)	(0.107)	(0.313)	(0.168)	(0.504)	(0.283)
Av. milk price in the municipio (real) * Dist. OPO	0.020**	0.003	0.029***	0.002	0.031***	0.004
	(0.009)	(0.004)	(0.009)	(0.004)	(0.010)	(0.005)
Av. Beef price in the municipio (real) * Dist. OPO	0.005	0.004	-0.004	-0.006	-0.009	-0.005
	(0.005)	(0.003)	(0.005)	(0.004)	(0.007)	(0.005)
Year fixed effects	No	No	Yes	Yes	Yes	Yes
Municipality trends	No	No	No	No	Yes	Yes
Controls	No	No	Yes	Yes	Yes	Yes
Household fixed effects	No	No	Yes	Yes	Yes	Yes
Number of observations	373	362	372	359	372	359
Number of households	150	160	150	160	150	160
R-squared	0.021	0.007	0.192	0.091	0.216	0.093

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, lot size (ha, GIS estimate) and household size.
Households in the "low" category have an initial forest cover equal or less than 21.6% of their total lot size.