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Analysis

Do forests provide watershed services for farmers in the humid tropics? Evidence from the Brazilian Amazon

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ABSTRACT

Forests are a key component of hydrological cycles, and thus deforestation is likely to affect the availability and quality of water for downstream agricultural production. However, in humid tropical regions where water is relatively abundant and the terrain is relatively flat, it is unclear whether these changes in ecosystem services matter to local farmers. We test whether the extent of forest in upstream drainage areas affects downstream farm production in an agricultural colonization zone in the Brazilian Amazon. We first estimate panel models of the output of milk, which is the primary farm product in our study region. We then test for effects on pasture stocking and cow productivity as possible pathways for the effect of upstream forests on milk output. Estimation results suggest that upstream forest increases the productivity of properties with small drainage areas. The effects are strongest when water is either scarce (dry season of drought years) or excessive (rainy season of flood years). The contribution of Amazonian forests to the resilience of the local farm economy is likely to become more important as rainfall becomes more variable due to regional and global climate change.

1. Introduction

Tropical deforestation affects ecosystem services at multiple scales. While impacts on global public goods such as biodiversity and climate stability have attracted the most attention in the scientific literature, impacts on locally valuable ecosystem services are more directly relevant to local decision-making about agricultural expansion into tropical forests. These include the effects of deforestation on watershed processes, such as evapotranspiration, sediment load, water chemistry, total flow, base flow, and groundwater recharge (Biggs et al., 2004; Gerten et al., 2005; Neill et al., 2001; Scanlon et al., 2007; Lele, 2009). While deforestation is widely believed to have negative effects on downstream water users, the scientific evidence is mixed, especially regarding the effects of deforestation on availability of surface and ground water for crops and livestock (Pattanayak and Kramer, 2001a, 2001b; Levy et al., 2018). Better evidence on whether forests compete with or maintain the supply and quality of water for downstream production could change the calculation of the net benefits of deforestation for local economic development, which is the priority of most local decision-makers (May et al., 2010).

The Brazilian Amazon has been deforested largely for cattle pasture and crop fields. The rate of deforestation in this region was among the highest in the world from 1988 to 2004, averaging 18,400 km^2 per year (INPE, 2020).[1] Although annual deforestation decreased from 27,000 km^2 in 2004 to 4500 km^2 in 2012 due partly to strong enforcement of land use policy, it has since risen to 10,129 km^2 in 2019 (INPE, 2020). We examine whether and how changes in watershed services due to this deforestation have affected the productivity of small-scale dairy farming in an agricultural colonization zone in the western Brazilian Amazon.

The Amazon forest is generally recognized as playing an important role in global hydrological cycles (Lovejoy and Nobre, 2018) and the regional water and energy balance (De Sales et al., 2020; Lima et al.,

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[1] Rates cited in this paragraph refer to deforestation in the Brazilian Legal Amazon, which spans over 5 million km^2, or nearly 60% of the Brazilian territory. The Legal Amazon was defined by the Brazilian government in 1966 (amended in 1977) for planning and administrative purposes.

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2014), but there remain questions about its significance for local agricultural production. This is partly because the effects of deforestation on stream flows, including flows in extreme dry and wet seasons, are not fully understood. Studies in various settings have found that deforestation increases flow due to the reduced evapotranspiration on deforested land (Bosch and Hewlett, 1982; Nóbrega et al., 2017; Levy et al., 2018). However, compaction of the surface can decrease dry season flow by decreasing recharge, and deforestation has been found to decrease dry season flows in some highly seasonal tropical catchments (Peña-Arancibia et al., 2019). Further, conversion of forests to agricultural land uses is often accompanied by other changes in the landscape, including construction of small reservoirs that can reduce downstream discharge, with larger impacts in dry years (Habets et al., 2018). On the other hand, the quantity of water available downstream may be determined almost entirely by precipitation and drainage size rather than forest cover.

There is also incomplete understanding of how changes in stream flows affect farm production. These effects are likely to be non-linear in the sense that when water is abundant, increases in stream flow may have a negative or no effect, whereas in conditions of water scarcity, small increases in stream flow can have important positive impacts on agricultural production (King, 1983; van Breugel et al., 2010). The small existing literature on the role of forest watershed services in agricultural production has focused on crop production in south and southeast Asia (Mullan, 2014; Barkmann et al., 2008; Lele et al., 2008; Pattanayak and Kramer, 2001a, 2001b). The availability and quality of water are likely to have very different relationships with livestock husbandry than with crop production. This is key in the Amazon, where cattle ranching dominates the deforested landscape, partly because it is suited to the strong annual dry seasons (Chomitz and Thomas, 2003; Sombroek, 2001).

Economic analysis of the value of forest ecosystem services for farmers has been conceptualized using a three-stage framework that links changes in the ecosystem, changes in ecosystem processes or functions, and changes in production, which are valued based on their contribution to profits and utility (Freeman, 1993; Pattanayak and Butry, 2003; Pattanayak, 2004; Ferraro et al., 2012). In the developing country context, the household production framework is commonly used to specify a model relating changes in ecosystems to the income of farm households. As further developed in the Supplemental Information (SI), we draw on the modeling framework of Pattanayak and Kramer (2001b), who derived the equivalence of the marginal willingness to pay (WTP) and the marginal production profits of the watershed service input ($dWTP = d\pi/dW$) under a producer-consumer household utility maximization framework. The WTP, or value of watershed services, is a function of the marginal output supply from the services. We lack data on the ecosystem processes or functions themselves. Therefore, we test whether and under what conditions the Amazon forest provides watershed services (or disservices) to smallholders by estimating the marginal effect of upstream forest cover on downstream output. Specifically, we test for an effect on milk output, because dairy is the mainstay of farmer livelihoods in our study region (Caviglia-Harris, 2018). We then examine the productivity of pastures and cows as potential pathways for the estimated effect of upstream forest on downstream milk output. Finally, we estimate the effect of forest on milk revenues, in order to gain insight on the economic value of the watershed services.

We combine data from four sources to estimate how forest watershed services affect the output and productivity of dairy farms. These are: (1) socioeconomic data from a four-wave farm household survey over a 14-year span; (2) hydrological data, including the full stream network and size of the drainage area of the three largest streams draining to each farm; (3) remote sensing data on the land cover of all farm properties and drainage areas in the study region over the 14 years; and (4) other spatial data, including property boundaries, road networks, market locations, and biophysical characteristics. The empirical analysis quantifies the marginal effect of forest in the upstream drainage area of a given property on downstream dairy production on that property.

This paper continue as follows. Section 2 describes our study region, and section 3 our collection and processing of data. Section 4 presents our empirical strategy. We begin by testing the effect of forest cover in the drainage area on the annual output of milk and then examine several dimensions of productivity that could explain this effect. We focus on the effect of forest cover in the drainage area outside the property to avoid endogeneity, but we confirm that the results are qualitatively similar for forest cover in the entire drainage area. Section 5 reviews our results, and Section 6 rules out the most likely rival explanation. We conclude in Section 7 that standing forest provides valuable watershed services for downstream dairy production on properties with small drainage areas, with the largest and most statistically significant effects when water is either scarce (in the dry season of drought years) or excessive (in the rainy season of flood years).

2. Study area

The Ouro Preto do Oeste (OPO) region of the northwestern Brazilian state of Rondônia includes six municipalities (Ouro Preto do Oeste, Vale do Paraíso, Urupá, Mirante da Serra, Nova União, and Teixeirópolis) connected to the central city of Ouro Preto do Oeste, located on federal highway BR-364 (Fig. 1). The total population in these six municipalities was just over 83,000 (46% rural) in 2010 (IBGE, 2010).

The OPO region is composed mostly of agrarian settlements typical of those established by the Brazilian federal government throughout the Amazon since the late 1960s. The federal agency INCRA (the National Institute for Colonization and Agrarian Reform) distributed forested lots in these settlements at little or no cost to new landowners, who were encouraged to migrate from southern and northeastern states (Moran, 1981). These settlements account for both most of the farm population and most of the deforestation in the Brazilian Amazon.

Migration to Ouro Preto do Oeste continued into the 1990s, motivated by relatively fertile soils and easy access to the region facilitated by the paving of the BR-364 inter-state highway. Unlike other parts of the Amazon, land tenure rights in the settlements in our study region are secure (Jones et al., 1995; Sills and Caviglia-Harris, 2009). During our study period (1996–2009), many of the original settlers remained in the region and still held the lots that INCRA originally allocated to them, meaning that both their location and their biophysical characteristics were fixed by that initial allocation process.

The major agricultural activities of the OPO region include raising dairy cattle and growing annual (maize, rice, beans, and manioc) and perennial (cacao, coconut and coffee) crops (Mullan et al., 2018). Income from milk is both the largest and the most regular source of agricultural income, facilitated by daily farmgate pick-up by numerous dairy plants in the region. Pasture creation has been the immediate motivation for most deforestation in the region, and nearly half (46.8%) of private land had been converted to pasture by 1996. This increased to 77.6% by 2009.

The region's climate is humid tropical, with an average temperature of 24°C and annual precipitation of 2300 mm. There is a distinct dry season from June to September (INPE, 2020; Caviglia-Harris et al., 2009). Production conditions differ between wet and dry season: water and fodder are abundant in the rainy season, while both are limited in the dry season, leading to depressed milk productivity (Freifelder et al., 1998; Neal et al., 2011; Doreau et al., 2013). There is evidence that both wet and dry seasons are becoming more extreme (Gloor et al., 2013), with earlier onset and longer durations of the dry season in the early 21st century in the southern Amazon (Marengo et al., 2011; Fu et al., 2013). The dry season may continue to intensify with regional climate warming (Boisier et al., 2015).

3. Data

We use four types of data in our analysis: household survey panel data (Caviglia-Harris et al., 2014), hydrological data, remote sensing

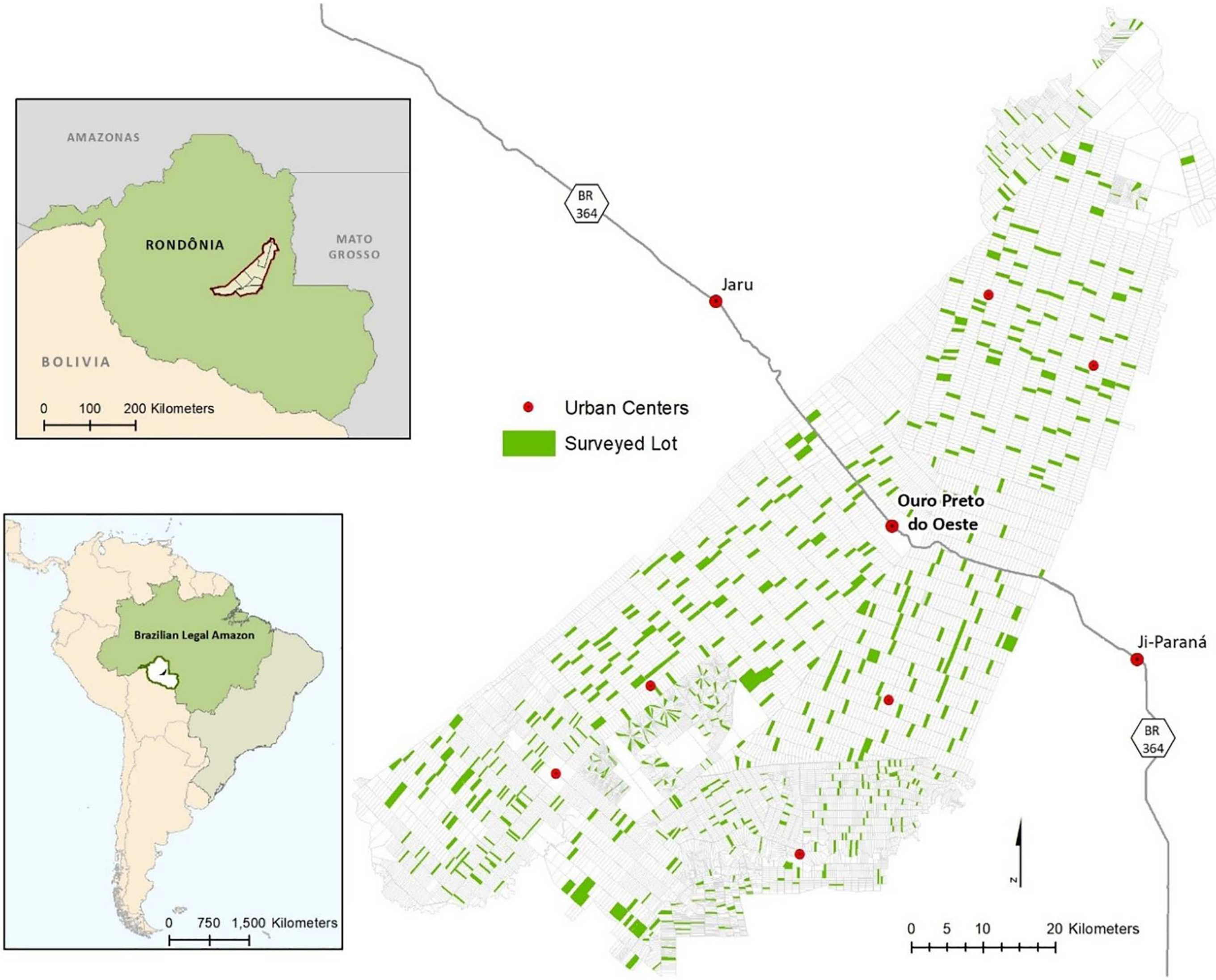


Fig. 1. Study area and landholdings of interviewed households.

land cover data (Roberts et al., 2002), and other spatial data. We merge and process these data in a GIS and export the relevant variables for analysis in Stata, as summarized in Table 1.

The survey data are from a panel of households interviewed in the dry seasons of 1996, 2000, 2005, and 2009. The households in the panel are a random sample stratified by municipality. The data set used in our analysis includes 309 households who were interviewed in at least two of the four survey waves, resulting in a four-year unbalanced panel.[2] We elicited information on the cattle herd, including the number of milk cows, the quantity of milk output, and revenues from milk production, to create the dependent variables listed in Table 1. Turning to the inputs listed in Table 1, household labor is a key production input in our study region. We proxy for household labor and human capital with average age and education level of the male and female household heads and the number of household members living on the lot. Due to generational turn-over, both mean age and education level of household heads increased slowly over survey waves, while the number of household members decreased.

Farmer decisions about how much to invest in productivity are likely driven in part by the farmgate price of milk, which we elicited for both dry and rainy seasons and adjusted for inflation. In general, the average real price of milk is higher in the dry season and increases over time. To fill in information on missing milk prices for households that reported no milk production in a given season and year, we employ the kriging geostatistical interpolation method to generate farmgate milk price surfaces for each survey year (Schabenberger and Gotway, 2017).[3] The interpolation is based on the premise that the known price "points" and the price surface at nearby locations are more similar to each other than price points at locations distant from each other.

The hydrological data include the full stream network, and the size of the drainage area for each farm, constructed from a Digital Elevation Model (DEM) based on 30-m data from the Shuttle Radar Topography Mission (SRTM-V2). Drainage areas are defined based on flow direction

[2] INCRA maps of the settlements were used as the sampling frame for each wave of the survey. We both tracked households who lived on the lots sampled in 1996 and drew supplementary samples in new settlements established after 1996. The sample expansion in follow-up waves compensated for attrition and maintained population representation (Caviglia-Harris, 2018). A balanced panel (142 households) was analyzed as well. The estimated marginal effects have the same signs and similar sizes, but are less often statistically significant, as compared with estimation results from the larger unbalanced panel. Results available upon request.

[3] Kriging was based on the Gaussian semivariance model.

Table 1
Descriptive statistics.

	Definition	Mean (standard deviation) 1996	2000	2005	2009
Dependent Variables					
Total milk production	Total milk produced in a year, thousand liter	16.87 (19.31)	26.39 (31.14)	21.87 (26.51)	26.45 (34.00)
Cow/ km^2	Dairy cows per km^2 of pasture	37.23 (39.29)	38.31 (38.91)	64.82 (101.68)	38.82 (39.67)
Milk/cow, dry	Liters of milk per day per cow in dry season	2.49 (2.45)	2.69 (1.81)	1.94 (2.53)	2.78 (3.13)
Milk/cow, wet	Liters of milk per day per cow in wet season	3.67 (3.98)	3.66 (2.68)	3.30 (3.05)	4.78 (7.06)
Milk/HA, dry	Liters of milk per day per hectare of pasture in dry season	0.90 (0.96)	1.23 (1.40)	1.18 (2.02)	1.27 (1.77)
Milk/HA, wet	Liters of milk per day per hectare of pasture in wet season	1.32 (1.50)	1.61 (1.74)	2.04 (3.52)	2.02 (2.75)
Milk revenue, dry	Milk revenues per day in dry season, R$2000[1]	7.21 (8.28)	17.02 (21.11)	11.21 (14.84)	16.82 (24.28)
Milk revenue, wet	Milk revenues per day in wet season, R$2000	10.81 (13.34)	15.82 (19.48)	20.15 (25.07)	21.15 (31.27)
Total milk revenue	Total milk revenues in a year, R$2000	3288.14 (3896.33)	5993.55 (7308.34)	5723.35 (7047.26)	6929.18 (9500.69)
Hydrologic Variables					
Drainage area	Total drainage area of the property, km^2	14.60 (32.42)	13.80 (31.97)	13.97 (29.81)	13.43 (28.73)
Drainage group	Binary variable; =1 for small drainage, =0 otherwise, where small is defined as drainages in the lowest tercile of drainage size.	0.31 (0.46)	0.32 (0.47)	0.34 (0.47)	0.35 (0.48)
Forest in drainage	Area of mature forest in the drainage area, km^2	5.31 (14.30)	3.76 (11.60)	2.84 (7.92)	2.06 (4.96)
Forest in off-lot drainage	Area of mature forest in the drainage that is not part of the same property, km^2	5.15 (14.29)	3.66 (11.59)	2.77 (7.91)	2.01 (4.95)
Water access	Dummy =1 for properties crossed by rivers and streams, 0 otherwise	0.35 (0.48)	0.33 (0.47)	0.32 (0.47)	0.30 (0.46)
Output Prices					
Milk price, dry	Farm gate price per liter of milk in the dry season, replaced with kriged milk price when missing, R $2000	0.19 (0.02)	0.27 (0.04)	0.25 (0.04)	0.29 (0.06)
Milk price, wet	Farm gate price per liter of milk in the wet season, replaced with kriged milk price when missing, R $2000	0.19 (0.02)	0.19 (0.05)	0.26 (0.04)	0.23 (0.04)
Proxies for Inputs					
Distance	Distance by road to closest urban center, km	15.01 (6.88)	15.04 (6.81)	15.29 (7.19)	15.26 (7.23)
Household age	Average age of the household heads, years	44.85 (13.30)	47.35 (12.54)	47.20 (14.08)	50.43 (14.07)
Household education	Average education level of the household heads, years	2.64 (2.46)	2.73 (1.79)	3.20 (2.15)	3.49 (2.69)
Household size	Number of household members living on the lot	8.65 (6.02)	7.18 (5.80)	5.61 (3.58)	5.11 (3.41)
Soil	Fraction of property characterized as having good soil for agriculture	0.03 (0.16)	0.02 (0.13)	0.02 (0.14)	0.02 (0.14)
Slope	Average slope of property, (0-50%)	4.06 (1.85)	4.08 (1.85)	4.04 (1.84)	4.04 (1.84)
Lot size	Size of lot, km^2	0.79 (0.39)	0.78 (0.40)	0.69 (0.40)	0.69 (0.41)
Lot age	Age of the property, years	19.35 (8.75)	22.93 (9.09)	25.36 (10.78)	29.28 (10.75)
Observations		176	177	293	291

Note:[1] The Purchasing Power Parity (PPP) was 0.759 Brazilian real (R$) per US dollar in 2000 (OECD).

and flow accumulation points identified at the intersection of the stream network and the boundary of each lot using the DEM. Based on flow accumulation (i.e. the number of upstream pixels), we identified the three largest drainage areas supplying each lot.[4] Drainage area reported in Table 1 is the sum across the drainages identified for each lot.[5] These may include intermittent drainages (having flowing water only during the wet season), ephemeral drainages (having flowing water only for brief periods in response to rainfall), and small unchanneled drainages.

Land cover maps were derived from annual Landsat imagery, following the methods described in Roberts et al. (2002). The forest cover in each drainage area upstream from the property (with and without the area of the drainage on the property itself) was determined for each year from the land cover maps. Because second-growth forest can be confused with poorly maintained pasture or perennial crops, we include only mature forest that has never been cleared. All other land covers are combined into a "deforested" category. As an example, Fig. 2 shows the boundaries of the drainage area for a 98-ha property in the municipality of Teixeirópolis. The drainage area is the union of the three largest drainage areas supplying the lot and covers 4940 ha, including 284 ha of mature forest.

In our study region, there are large temporal variations in water availability driven by variation in precipitation. As shown in Fig. 3,

[4] A small number of lots did not contain three separate drainage areas. Either one or two drainage areas were identified in these cases. Additionally, several lots had no flow accumulation difference between the 3rd and 4th drainage areas. In these cases, we selected four drainage areas for the analysis.

[5] Seven properties with drainages larger than 200 km^2 were considered outliers and excluded from the analysis.

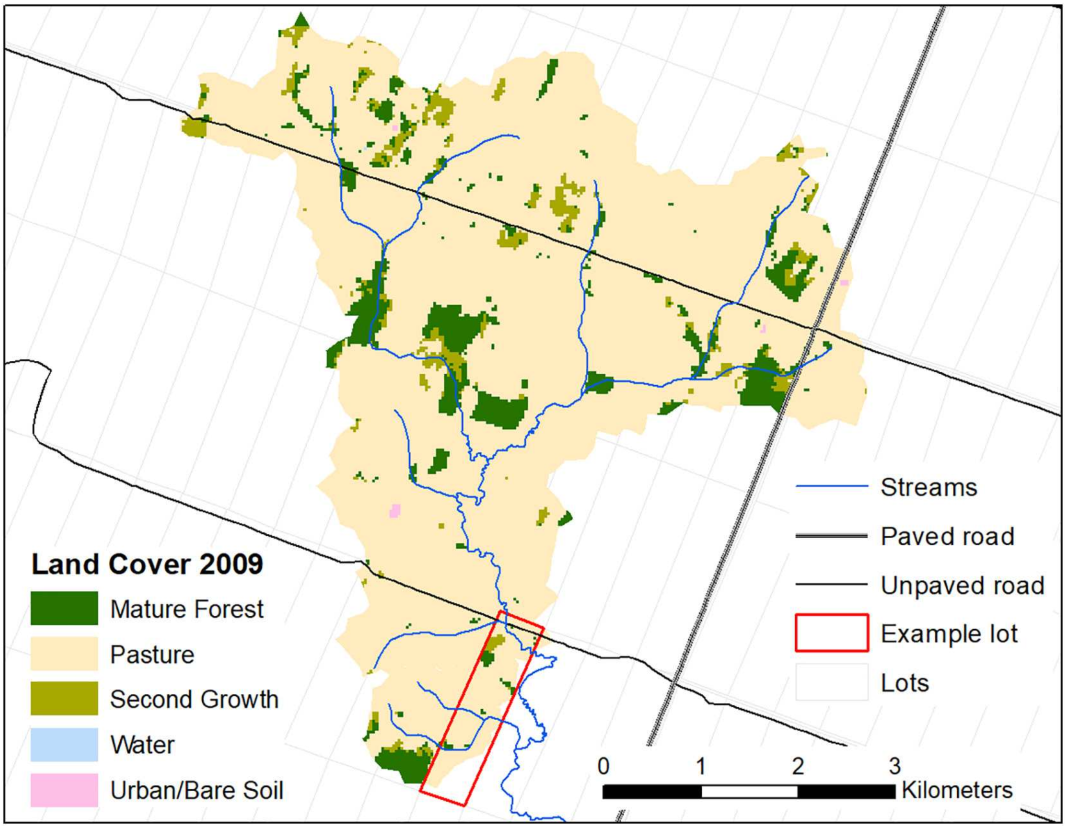


Fig. 2. Land cover in drainage area of an example lot.

among the survey years, 2005 had the extreme lowest stream flow and precipitation. The wet season of 2009 had the highest precipitation. In the empirical analysis, we use year dummy variables to capture these temporal changes in water availability.

Other spatial data include property characteristics that are important fixed inputs to production: size of the property, soil quality, average slope, and age (the number of years since deforestation of the property began). To generate these data, property boundaries were digitized from INCRA settlement maps in 2000 and updated with more recent INCRA subdivisions and field measurements of a sample of boundary corners in 2005 and 2009. To establish the age of properties with forest cleared before 1985 (the first year of our remote sensing data), we relied on the official settlement records from INCRA. A soil layer was obtained from the Brazilian Agricultural Research Corporation (EMBRAPA, 1983) and used to determine the fraction of each lot with soil considered good for agriculture. Average slope for each lot was determined with the DEM.

We proxy for prices of variable inputs using distance to the nearest urban center, calculated as the minimum travel distance along the road network.[6] Road networks were constructed through GPS field data collection in 2005 and 2009 during travel over 1400 km of roads. The roads not directly collected by GPS were digitized from INCRA settlement maps and high-resolution imagery in Google Earth.

Our nine dependent variables are derived from the household survey and remotely sensed land cover data. Because some households do not have any dairy cows and therefore do not produce milk (in any year), all of these variables have a probability mass at zero. Milk output (1) is the total milk produced in a year, including dry and wet seasons. Stocking density (2), an indicator of the productivity of pasture, is number of dairy cattle as stated in the survey divided by areas of pasture as identified via remote sensing. Productivity of the cows is measured as liters of milk per day per dairy cow in the dry (3) and wet seasons (4). This outcome is set at zero for households with no dairy cows, same as for total milk output and milk produced per hectare of pasture. We also model the total productivity of the system measured as liters of milk per day per hectare of pasture in the dry (5) and wet seasons (6). To explore the value of forest watershed services, we estimate models of daily revenues from milk in the dry season (7) and wet season (8) and total milk revenues in a year (9).[7] Most of these dependent variables increased steadily across survey waves, with the exception of the severe drought year of 2005.

4. Empirical strategy

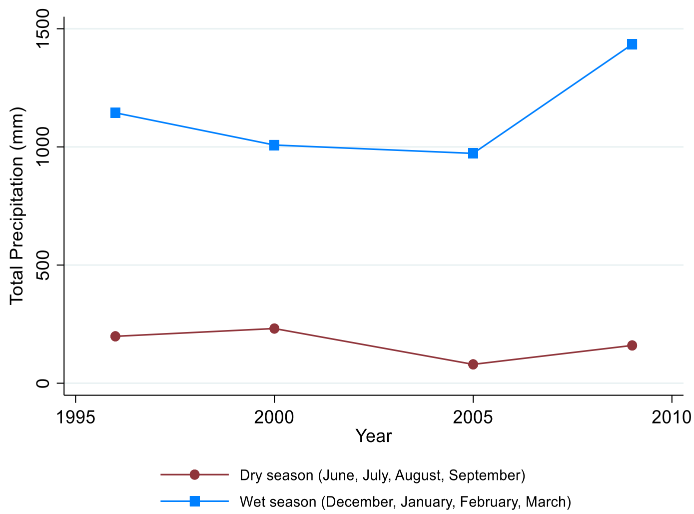
The empirical analysis aims to quantify the marginal effect of forest in the upstream drainage of a given property on milk production on that property. Milk is the dominant agricultural production activity and therefore the primary agricultural output over which households make utility and profit optimization decisions. To avoid selection bias, we estimate our models of milk output and productivity using data from all households, including those with no milk production.

We first estimate an output supply function to test the marginal effect of forest in the drainage. As shown in the SI, output supply is a function of output price, variable input prices, fixed inputs, and household characteristics. Thus, we model farm i's milk output in time period t, Q_{it}, as follows:

[6] This strategy is supported by the positive correlation between distance to nearest urban center and prices of variables inputs that were reported by households.

[7] We model revenues rather than profits, because profits are subject to measurement errors related to the lack of consistent data on variable costs that are not incurred every year.

Fig. 3. Precipitation and low-flow in the Study Area.
A. Total precipitation in dry and wet seasons.
These are precipitation totals during 4 month dry and wet seasons measured at Mirante, Jaru, and Rondominas weather stations (ANA, 2017).
B. Low-flow at river gauges.
Low-flow is the mean of the 10% lowest daily stream flows for each survey year at gauges on two rivers in the study area (Jaru and Jamari).



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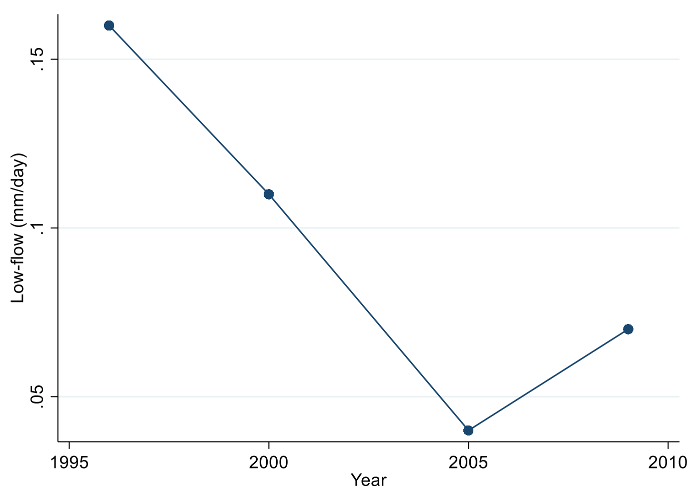

B. Low-flow at River Gauges

Low-flow is the mean of the 10% lowest daily stream flows for each survey year at gauges on two rivers in the study area (Jaru and Jamari).

$$Q_{it} = f\left(W_{it}, P_{it}, P_{it}^{V}, Z_{it}, H_{it}, \varepsilon_{it}\right) \quad (1)$$

where W_{it} represents hydrological inputs (watershed services) for farm i in the year t, P_{it} is the output price of milk,[8] P_{it}^{V} represents a vector of variable of input prices, Z_{it} represents a vector of fixed inputs, H_{it} represents a vector of household characteristics, and ε_{it} is the error term. Input prices, fixed inputs, and household characteristics are represented by the proxies described in the data section, and fixed effects for municipalities are also included. The dependent variables and all explanatory variables with skewed distributions or extreme values are transformed by inverse hyperbolic sine (IHS).[9] Next, we examine the possible ways that upstream forest can affect output by testing whether forest in the drainage influences pasture, cow, or total productivity of dairy production, including the same controls as for output supply. Finally, to approximate the marginal value of watershed services, we estimate a revenue function of milk as a function of output price and all types of inputs.

Hydrological inputs W_{it} are represented as the size of the area that drains to a given property (upstream drainage size) and the portion of that area covered by mature forest (Stuckey, 2006; Jones et al., 2017). Fixed effects for years capture rainfall, since we only observe annual – and not spatial – variation. The main parameter of interest in this paper is the marginal effect of mature forest cover upstream of a property. We begin by estimating the marginal effects of the proportion of the drainage under forest cover, conditional on but not interacted with the drainage size or year fixed effects, and then we add a full set of interaction terms to allow for nonlinear relationships. For simplicity of interpretation, we categorize the upstream drainage size into two groups, small and large drainages, and create a categorical variable, drainage group. The cutoff point is 1.7 km^2, which defines the lowest tercile of drainage size.[10] Based on field observations in Rondônia in August 2017, most drainages in that lowest tercile had no dry season streamflow (unpublished data). To fully capture the factors influencing water intake of cows,[11] we also control for access to other water sources on the property such as rivers and streams.

Farmers typically own and make land use decisions for part of the drainage that supplies their property. This creates potential endogeneity between production outcomes and land use in the drainage. For example, if farmers recognized that forest in the drainage affects production on their property, they would be expected to manage the drainage area differently from the rest of the property. However, in the SI, we show that there is no difference in forest cover in the portions of the property inside and outside the drainage area. A Durbin-Wu-Hausman test (Davidson and MacKinnon, 1995) also suggests that forest in the whole drainage is not endogenous. Thus, we focus on the effect of forest in the portion of the upstream drainage that is located off the farm lot, since that is clearly exogenous, but we also test robustness of our effect estimates to using forest in the entire drainage.

Due to the possibility of zero milk production, the dependent variable is semi-continuous, combining a continuous distribution with a point-mass at zero (Olsen and Schafer, 2001). Simply omitting the observations with no milk cows or milk production would generate selection bias (Heckman, 1979). We assume that decisions about how much to produce are not meaningfully different from decisions about whether to produce, and we proceed by jointly estimating the probability of production and the output supply (Sadoulet and De Janvry, 1995). Thus, we estimate a censored Tobit model.

Our data contain observations of the same farm households over at least two time periods, suggesting that we could include fixed effects for households. However, for the Tobit model, there is no sufficient statistic allowing the fixed effects to be conditioned out of the likelihood, and unconditional fixed-effects estimates are biased (Greene, 2004; StataCorp, 2015). Hence, we proceed by integrating random effects into a Tobit model, while also including dummy variables for year and municipality to control for temporal and spatial correlation in the error term. The unobserved latent dependent variable Y_{it}^{*} is defined as:

$$Y_{it}^{*} = \alpha + \beta' X + u_i + e_{it} \quad (2)$$

The observed dependent variable Y_{it} is:

$$Y_{it} = \begin{cases} Y_{it}^{*} \; if \; Y_{it}^{*} > 0 \\ 0 \; if \; Y_{it}^{*} = 0 \end{cases} \quad (3)$$

where $X = [W_{it}, P_{it}, P_{it}^{V}, Z_{it}]$ is a covariate matrix, u_i is an unobserved individual specific time invariant effect, e_{it} is the remainder disturbance, and α is a constant. We also estimate pooled Tobit models with cluster-robust standard errors for comparison.

5. Results

Average marginal effects on the observed dependent variables transformed by IHS (Y_{it}) are reported in Tables 2–4. Marginal effects are generally consistent across the random effects and pooled models.

Table 2 presents estimation results for models of milk output and productivity (measured as stocking rate, milk production per cow, and milk production per hectare of pasture). In these models, the effect of mature forest in the upstream drainage located off the farm lot is conditioned on, but not interacted with, the drainage size and year temporal effects (both proxies for the total quantity of water available).

The year effects are all negative, with the lowest values for milk/cow and milk/pasture in 2005. Given that we control for property age and other influences on production that change over time, such as farmer education and milk prices, the year dummy variables capture the remaining temporal variation. This includes precipitation and dry season stream flow, which were lowest in 2005, followed by 2009. Another determinant of water availability, the area of the upstream drainage, does not have a significant effect in the dry season, but does have a significantly negative effect on productivity in the rainy season.

The primary variable of interest, upstream forest off the farm lot, is significantly and positively related to milk output and productivity of the pasture as measured by the stocking rate and milk production per hectare of pasture. While larger drainage areas and the associated higher water flow decreases productivity in the rainy season, forest cover in the drainage mitigates the negative effects of too much water. Large drainage areas may be associated with lower production in the wet season due to poor soil quality along floodplains, which are typically sandy and do not support grass production, and/or more water logging (the saturation of soil with water) of pasture along large streams and during wet years. Common pasture grasses in the Amazon, including the Brachiaria genus, are sensitive to water logging, and water logging for as little as 14 days can reduce growth and biomass production (Dias-Filho and De Carvalho, 2000).

Marginal effects of covariates generally have expected signs, with

[8] The farmers are considered to be price-takers and the milk price to be exogenous.

[9] The inverse hyperbolic sine (IHS) transformation is an alternative to natural log transformation for variables with both extreme values and zero or negative values (Burbidge et al. 1988). It can be interpreted in the same way as a natural log transformation (Pence, 2006; Friedline et al., 2015).

[10] Given uncertainty in this threshold drainage area for specific places and times, we examine the sensitivity of our results to this cut-off point. The magnitude of the marginal effect of upstream forest in small drainages generally decreases with higher cutoff points. The effects of upstream forest off lot on total milk output in both seasons and productivity in wet season become insignificant with higher cutoff points. The effects on productivity in dry season become less statistically significant ($p < 0.1$) with higher cutoff points. This suggests that the lowest tercile of drainage size effectively differentiates drainages according to the role of forest cover downstream outcomes.

[11] The water intake of cows would be influenced by temperature as well. However, the effect of temperature, which is invariant across farms in the region, is swept out of the regressions by the year fixed effects.

Table 2
Marginal effects of upstream (off-lot) forest: no interaction terms.

	Total milk production		Cows/pasture		Milk/cow, dry		Milk/cow, wet		Milk/pasture, dry		Milk/pasture, wet	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
Forest in off-lot drainage	0.185**	0.171*	0.098***	0.090**	0.151*	0.154*	0.176**	0.169**	0.147**	0.145*	0.171**	0.160**
	(0.092)	(0.094)	(0.036)	(0.039)	(0.078)	(0.084)	(0.079)	(0.082)	(0.071)	(0.075)	(0.072)	(0.074)
y2000	-1.654***	-1.650***	-0.417*	-0.408*	-1.379***	-1.380***	-1.558***	-1.562***	-1.150***	-1.162***	-1.183***	-1.189***
	(0.548)	(0.559)	(0.219)	(0.218)	(0.464)	(0.467)	(0.417)	(0.447)	(0.414)	(0.420)	(0.376)	(0.402)
y2005	-1.861***	-1.737***	0.005	0.044	-2.223***	-2.143***	-1.930***	-1.887***	-1.752***	-1.680***	-1.452***	-1.434***
	(0.569)	(0.575)	(0.225)	(0.232)	(0.481)	(0.490)	(0.523)	(0.516)	(0.434)	(0.445)	(0.474)	(0.473)
y2009	-2.500***	-2.350***	-0.715**	-0.657**	-1.845***	-1.733***	-2.182***	-2.097***	-1.706***	-1.604***	-1.868***	-1.802***
	(0.732)	(0.726)	(0.289)	(0.287)	(0.620)	(0.628)	(0.569)	(0.578)	(0.560)	(0.565)	(0.517)	(0.522)
Drainage area	-0.344*	-0.297	-0.173**	-0.148**	-0.264	-0.251	-0.333*	-0.312*	-0.233	-0.213	-0.290*	-0.263*
	(0.202)	(0.182)	(0.079)	(0.074)	(0.171)	(0.159)	(0.173)	(0.160)	(0.157)	(0.142)	(0.158)	(0.143)
Water access	0.673	0.612	0.300*	0.280*	0.547	0.523*	0.579	0.530*	0.543	0.526*	0.551	0.514*
	(0.463)	(0.374)	(0.180)	(0.143)	(0.390)	(0.311)	(0.396)	(0.319)	(0.360)	(0.279)	(0.363)	(0.288)
Milk price	4.276	4.218	2.182	2.041*	2.709	2.624	-0.322	0.496	4.035	4.046*	0.802	1.864
	(3.471)	(2.791)	(1.385)	(1.197)	(2.938)	(2.358)	(3.396)	(2.623)	(2.630)	(2.175)	(3.067)	(2.386)
Distance	-0.007	-0.094	0.177	0.126	-0.118	-0.178	-0.022	-0.079	-0.002	-0.075	0.066	-0.002
	(0.393)	(0.364)	(0.153)	(0.145)	(0.332)	(0.305)	(0.336)	(0.312)	(0.306)	(0.273)	(0.308)	(0.280)
Household age	0.052***	0.049***	0.020***	0.018***	0.036***	0.032**	0.038***	0.034**	0.035***	0.032***	0.037***	0.034***
	(0.014)	(0.016)	(0.006)	(0.006)	(0.012)	(0.013)	(0.012)	(0.013)	(0.011)	(0.012)	(0.011)	(0.012)
Household education	0.011	0.008	-0.002	0.007	-0.035	-0.045	-0.003	-0.007	-0.016	-0.018	0.011	0.016
	(0.080)	(0.086)	(0.032)	(0.034)	(0.068)	(0.072)	(0.069)	(0.074)	(0.061)	(0.065)	(0.063)	(0.067)
Household size	0.098***	0.131***	0.045***	0.057***	0.077**	0.104***	0.081**	0.111***	0.065**	0.094***	0.071**	0.100***
	(0.036)	(0.041)	(0.014)	(0.014)	(0.031)	(0.034)	(0.032)	(0.035)	(0.028)	(0.030)	(0.029)	(0.032)
Soil	0.536	0.576	0.173	0.229	0.296	0.330	0.494	0.524	0.285	0.366	0.495	0.573
	(1.430)	(0.902)	(0.558)	(0.388)	(1.205)	(0.702)	(1.227)	(0.750)	(1.112)	(0.632)	(1.123)	(0.680)
Slope	-0.019	0.050	0.027	0.097	-0.200	-0.116	-0.193	-0.173	0.004	0.113	0.036	0.080
	(0.658)	(0.580)	(0.256)	(0.227)	(0.556)	(0.483)	(0.565)	(0.505)	(0.513)	(0.441)	(0.517)	(0.459)
Lot size	-1.230**	-1.099**	-0.731***	-0.708***	-0.705*	-0.650	-1.501***	-1.413***	-0.938**	-0.891**	-1.650***	-1.575***
	(0.505)	(0.477)	(0.196)	(0.187)	(0.429)	(0.435)	(0.433)	(0.416)	(0.393)	(0.398)	(0.395)	(0.379)
Lot age	0.119***	0.115***	0.019	0.017	0.072**	0.072**	0.107***	0.107***	0.067**	0.065**	0.098***	0.097***
	(0.035)	(0.034)	(0.014)	(0.013)	(0.030)	(0.031)	(0.030)	(0.030)	(0.027)	(0.029)	(0.028)	(0.028)
Municipality (spatial) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
number of Observations	933	933	933	933	933	933	933	933	933	933	933	933

Notes: The cells report the average marginal effects (the average of individual marginal effects) on the observed dependent variable, with standard errors in parentheses.
The first row indicates the six dependent variables.
The IHS transformation was applied to all dependent variables and continuous independent variables with skewed distributions: forest in off lot drainage; drainage area; distance; slope; and lot size.
In the regression of lHS(total milk production) and lHS(cow/pasture), "milk price" represent the average values for dry and rainy seasons. In the regression of lHS(milk/cow, dry) and IHS(milk/pasture, dry), "milk price" represents values in the dry season. In the regression of lHS(milk/cow, wet) and IHS(milk/pasture, wet), "milk price" represents values in the wet season.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table 3
Marginal effects of upstream (off-lot) forest: three-way interaction.

	Total Milk Production		Cow/pasture		Milk/cow, dry		Milk/cow, wet		Milk/pasture, dry		Milk/pasture, wet	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
Forest in off-lot drainage by year and drainage group												
1996 S	-0.202	-0.108	-0.012	0.023	-0.227	-0.136	-0.204	-0.135	-0.141	-0.049	-0.114	-0.044
	(0.240)	(0.144)	(0.095)	(0.073)	(0.208)	(0.121)	(0.213)	(0.138)	(0.186)	(0.106)	(0.191)	(0.123)
1996 L	-0.405	-0.406	-0.172	-0.166	-0.373	-0.348	-0.28	-0.268	-0.326	-0.317	-0.25	-0.253
	(0.399)	(0.325)	(0.155)	(0.14)	(0.343)	(0.278)	(0.348)	(0.283)	(0.309)	(0.248)	(0.314)	(0.254)
2000 S	0.152	0.138	0.102	0.088	0.116	0.114	0.134	0.135	0.1	0.083	0.114	0.102
	(0.163)	(0.232)	(0.067)	(0.099)	(0.14)	(0.193)	(0.142)	(0.2)	(0.126)	(0.176)	(0.129)	(0.182)
2000 L	-0.160	-0.154	-0.142	-0.132	-0.174	-0.142	-0.045	-0.02	-0.154	-0.137	-0.052	-0.041
	(0.376)	(0.372)	(0.146)	(0.139)	(0.321)	(0.309)	(0.325)	(0.319)	(0.291)	(0.279)	(0.294)	(0.289)
2005 S	0.220*	0.192	0.118**	0.104*	0.205**	0.192	0.186*	0.172	0.206**	0.188	0.190*	0.173
	(0.128)	(0.139)	(0.052)	(0.057)	(0.105)	(0.138)	(0.111)	(0.12)	(0.096)	(0.129)	(0.101)	(0.111)
2005 L	-0.357	-0.346	-0.164	-0.164	-0.275	-0.249	-0.326	-0.292	-0.256	-0.239	-0.305	-0.284
	(0.309)	(0.256)	(0.123)	(0.108)	(0.258)	(0.214)	(0.265)	(0.22)	(0.235)	(0.197)	(0.242)	(0.204)
2009 S	0.321**	0.290*	0.141***	0.125*	0.238**	0.242*	0.320 ***	0.305 **	0.221**	0.216*	0.294 ***	0.271 **
	(0.130)	(0.158)	(0.052)	(0.071)	(0.113)	(0.131)	(0.113)	(0.136)	(0.102)	(0.121)	(0.103)	(0.126)
2009 L	-0.339	-0.300	-0.079	-0.073	-0.33	-0.281	-0.283	-0.231	-0.26	-0.223	-0.221	-0.185
	(0.309)	(0.281)	(0.12)	(0.11)	(0.262)	(0.237)	(0.267)	(0.245)	(0.237)	(0.211)	(0.242)	(0.22)

Notes: These are average marginal effects (average of individual marginal effects) on the observed dependent variable, with standard errors in parentheses.
The IHS transformation was applied to all dependent variables and continuous independent variables with skewed distributions. Regressions include the same controls as in the Table 2.
"S" represents small drainage, and "L" represents large drainage.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% level.

Table 4
Milk revenues as a function of forest in off-lot drainage.

	Milk revenues per day, dry		Milk revenues per day, wet		Total milk revenues	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
A. no interaction						
Forest off lot	0.048	0.049	0.059*	0.056*	0.160**	0.148*
	(0.031)	(0.031)	(0.032)	(0.032)	(0.080)	(0.081)
B. year* drainage group*forest in off-lot drainage						
1996 S	-0.061	-0.016	-0.060	-0.015	-0.168	-0.083
	(0.068)	(0.043)	(0.075)	(0.056)	(0.206)	(0.122)
1996 L	-0.151	-0.165	-0.148	-0.163	-0.348	-0.352
	(0.128)	(0.103)	(0.137)	(0.110)	(0.345)	(0.279)
2000 S	0.030	0.021	0.034	0.029	0.128	0.115
	(0.052)	(0.073)	(0.053)	(0.073)	(0.141)	(0.200)
2000 L	-0.081	-0.089	-0.054	-0.059	-0.142	-0.139
	(0.129)	(0.126)	(0.132)	(0.128)	(0.327)	(0.321)
2005 S	0.064*	0.058	0.070	0.063	0.189*	0.164
	(0.039)	(0.049)	(0.044)	(0.048)	(0.111)	(0.122)
2005 L	-0.122	-0.119	-0.170	-0.163*	-0.317	-0.308
	(0.102)	(0.085)	(0.110)	(0.095)	(0.269)	(0.223)
2009 S	0.087**	0.080	0.113**	0.097*	0.282**	0.254*
	(0.042)	(0.051)	(0.044)	(0.053)	(0.113)	(0.137)
2009 L	-0.114	-0.100	-0.103	-0.088	-0.292	-0.258
	(0.105)	(0.094)	(0.111)	(0.101)	(0.269)	(0.244)

Notes: These are average marginal effects (average of individual marginal effects) of IHS transformed mature forest cover upstream on the observed dependent variable, with standard errors in parentheses. Regressions include the same controls as in the Table 2. The IHS transformation was applied to all dependent variables and continuous independent variables with skewed distributions.
"S" represents small drainage, and "L" represents large drainage.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

two exceptions. Total production declines with size of property and increases with the age of the property. Property size has a substantial negative effect on the productivity of milk cows and pasture, especially in the wet season. This could reflect more intensive management and hence a greater productivity bump in the wet season on small properties, consistent with the inverse relationship between size and productivity that has been found in a large body of empirical literature (Kutcher and Scandizzo, 1981; Kumbhakar, 1993; Graeub et al., 2016). Lot age has a positive effect on milk production, again primarily manifest in positive effects on productivity in the wet season. This could reflect the accumulation of capital, including both human and physical, over time.

Table 3 presents the marginal effects of mature forest upstream in models with three-way interactions of the watershed services determinants (*IHS*(*forest*) × *year dummy* × *drainage group*), including the same control variables as in Table 2. When we disaggregate the forest effect in this way, we find significantly positive effects of upstream forest cover on downstream milk production for farm properties fed by small drainages (less than 1.7 km^2). These are largest and most significant in the dry season of a drought year (2005) and the wet season of a flood year (2009). In 2005, a 10% increase in forest area in the drainage off lot led to a 2.20% increase in the total milk output of farms supplied by small drainage areas. This occurred due to an increase in milk production per cow and per hectare of pasture in the dry season, which increase by 2.05% and 2.06% respectively with a 10% increase in forest cover. On the other hand, the rainy season of the year 2009 brought floods due to extreme high precipitation. In that year, 10% more forest in small drainages was associated with 3.21% more milk output, and higher productivity, most significantly in the rainy season.

The marginal effects of upstream forest suggest that in large drainages, or in years with typical weather (no droughts or floods), upstream forest cover does not affect downstream farm production. However, for farm properties fed by small drainages, the proportion of the drainage in mature forest cover is significantly positively related to milk output and productivity, especially when water is scarce or excessive. In general, forest cover is more likely to have a significant impact on hydrological outcomes in small drainages. Properties along larger streams may be less sensitive to upstream land cover since their water flow is largely determined by precipitation over the entire river basin.

The non-linearities in the results suggest that there are multiple processes through which deforestation affects production downstream. In the dry season, particularly in drought years, small drainages are most likely to have ephemeral streams that dry up. The resulting water scarcity may be mitigated by upstream forests, consistent with Wang et al. (2019) but in contrast to other evidence that deforested areas have consistently more dry season and annual runoff than forested areas in both large (Levy et al., 2018) and small watersheds (Nóbrega et al., 2017; Williams and Melack, 1997). Alternatively, the positive impact of forest could be due to the absence of other upstream activities that occur following deforestation, such as construction of small reservoirs that can reduce dry season flow (Habets et al., 2018) and agricultural and aquaculture activities that can degrade water quality. In the rainy season of flood years, when there is excess water, forests reduce and slow overland flow by increasing infiltration rates, thereby reducing flooding and inundation downstream, potentially leaving more pasture available for grazing and reducing water logging along small floodplains. The effect is strongest in small watersheds, because runoff, including dry season baseflow and stormflow, is more sensitive to land cover in small watersheds (Rodriguez et al., 2010), while land use impacts on runoff are often not measurable in large watersheds (Zhang et al., 2012). Our results imply that upstream forest cover increases milk production in small watersheds, with further research required to determine the mechanisms linking forest cover, small reservoirs, water quality and quantity, and milk production.

To gain insight on the monetary value of forest watershed services, our final estimation is a milk revenue function. Consistent with the models of milk output, for farm properties with small drainages, the marginal effects of upstream forest on milk revenue are significantly positive in 2005 and 2009. Based on the estimated effects in Table 4, panel B, column 6, a 10% increase in upstream forest cover is associated with a 1.89% - 2.82% increase in total milk revenue in those drought and flood years. For the properties with small drainages and average forest cover, milk revenue would have been R$3.91 – R$9.72 (2010 PPP US $6.52–16.22/ha/year/property[12]) higher in a drought or flood year with an additional hectare of forest in their drainage areas. Because drainages can overlap and be nested in each other, each hectare of forest may affect multiple downstream properties. We estimate that in our study region, three downstream lots are affected by deforestation of a single pixel in small drainages.[13] This suggests that the marginal value of forest watershed services for local dairy production is about R$11.72 – R $29.16/ha/year (2010 PPP US$ 19.55–48.67/ha/year), which is equivalent to 8.74%–21.76% of average annual milk revenues per hectare of pasture. Thus, the marginal value of a hectare of forest as an input to downstream milk production is far less than the marginal value of a hectare of pasture (both calculated based on annual revenues from milk). Given low deforestation costs, this in turn suggests that even if farmers are aware of forest watershed services, they may still prefer to convert forest to pasture. This is consistent with the evidence presented in the SI that farmers deforest the area of their lot inside its drainage at the same rate as the rest of the lot.

In addition to the effect of forest in the upstream drainage off the farm lot, we test the effect of forest in the whole drainage, including the portion on the lot itself. The effects of forest in the whole drainage are qualitatively similar to the effects of forest in the portion of the upstream drainage located off the lot. Although the average effects of forest in the whole drainage across all years and all sizes of drainages are not statistically significant, we find significantly positive effects of upstream forest cover on downstream milk production for farm properties fed by small drainages in drought and flood years (Table B1–B2 in Appendix B). Since the drainage area within the household's own lot is subject to household land use and production decisions, we test for, but do not find, endogeneity. In the Durbin-Wu-Hausman test, the coefficient of the residuals on the potentially endogenous variable, upstream forest on lot, is not significantly different from zero in the augmented regression (Table B3 in Appendix B).

6. Testing a rival explanation

A possible alternative explanation for why forest cover in small – but not large - drainages influences downstream production is that the forests in small watersheds may be closer to the property than forests in large watersheds. It could be beneficial to have forest nearby, for example, because trees break the wind and provide shade for cattle. We rule out this possibility by testing the effect of forest cover in a 1 km buffer around the lot, which includes both upstream and downstream land, and comparing it with the estimated effect of upstream forest cover in small drainages (Table 5). Forest cover in the buffer generally does not have a statistically significant effect, and when significant, the effects on productivity, stocking, and total production are negative. This supports our interpretation of the positive relationship between dairy productivity and upstream forests in small drainage areas is driven by hydrological processes rather than other influences of nearby forests.

[12] The conversion rate of 2000 Purchasing Power Parties (PPP) for Brazilian real per US dollar is 0.759 (OECD) and the CPI in year 2010 and 2000 are 218.1 and 172.2 respectively (U.S. Bureau of Labor Statistics).

[13] To estimate the number of downstream lots that are affected by deforestation of a single hectare in small drainages, we randomly selected 12 pixels (2 in each municipality) in small drainages feeding lots in our survey sample, and then counted the number of small drainages that include each of those pixels. On average, a given pixel falls into three small drainages.

Table 5
Marginal effects of forest in the 1km buffer.

	Total milk production		Cow/pasture		Milk/cow, dry		Milk/cow, wet		Milk/pasture,dry		Milk/pasture,wet	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
A. no interaction forest 1km buffer												
	-0.247	-0.174	-0.0781	-0.048	-0.222	-0.157	-0.119	-0.044	-0.222	-0.150	-0.145	-0.065
	(0.304)	(0.277)	(0.119)	(0.106)	(0.257)	(0.233)	(0.262)	(0.239)	(0.233)	(0.211)	(0.239)	(0.216)
B. year*drainage group*forest 1km buffer forest 1km buffer by year and drainage group												
1996 S	-1.891*	-1.511	-0.702*	-0.582	-1.502	-1.110	-1.359	-1.080	-1.512*	-1.120	-1.374	-1.094
	(1.072)	(0.953)	(0.425)	(0.433)	(0.932)	(0.841)	(0.956)	(0.889)	(0.827)	(0.740)	(0.855)	(0.784)
1996 L	-2.241*	-1.671*	-0.884*	-0.655	-1.734	-1.271	-1.556	-1.165	-1.609*	-1.144*	-1.460	-1.078
	(1.240)	(0.962)	(0.489)	(0.408)	(1.067)	(0.789)	(1.091)	(0.835)	(0.947)	(0.692)	(0.978)	(0.736)
2000 S	-0.657	-0.438	-0.060	0.004	-0.515	-0.294	-0.340	-0.131	-0.623	-0.415	-0.470	-0.275
	(0.759)	(1.007)	(0.314)	(0.426)	(0.653)	(0.860)	(0.667)	(0.891)	(0.583)	(0.770)	(0.599)	(0.799)
2000 L	1.291	1.465	0.275	0.334	0.991	1.138	1.187	1.323	0.937	1.078	1.127	1.258
	(0.959)	(1.269)	(0.374)	(0.398)	(0.820)	(1.029)	(0.837)	(1.055)	(0.733)	(0.929)	(0.754)	(0.955)
2005 S	0.163	0.257	0.268	0.303	0.086	0.182	0.245	0.350	0.109	0.206	0.216	0.318
	(0.517)	(0.563)	(0.211)	(0.245)	(0.421)	(0.484)	(0.450)	(0.485)	(0.384)	(0.464)	(0.411)	(0.463)
2005 L	0.508	0.460	0.095	0.101	0.176	0.133	0.277	0.268	0.210	0.169	0.305	0.299
	(0.510)	(0.558)	(0.204)	(0.168)	(0.426)	(0.475)	(0.441)	(0.490)	(0.386)	(0.429)	(0.401)	(0.444)
2009 S	-0.384	-0.297	-0.171	-0.156	-0.187	-0.097	-0.001	0.061	-0.318	-0.200	-0.163	-0.079
	(0.529)	(0.526)	(0.209)	(0.210)	(0.456)	(0.447)	(0.462)	(0.475)	(0.411)	(0.414)	(0.419)	(0.438)
2009 L	-0.971*	-0.824*	-0.303	-0.249	-0.774*	-0.685*	-0.792*	-0.662*	-0.711*	-0.607*	-0.751*	-0.616*
	(0.505)	(0.429)	(0.199)	(0.173)	(0.429)	(0.357)	(0.438)	(0.372)	(0.384)	(0.316)	(0.395)	(0.332)

Notes: These are average marginal effects (the average of the individual marginal effects) of IHS transformed mature forest cover within 1 km buffer of the lot on the observed dependent variable, with standard errors in parentheses. Regressions include the same controls as in the Table 2.
"S" represents small drainage, and "L" represents large drainage.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

7. Conclusions

This paper examines local watershed services from forests in the humid tropics, thus contributing to the literatures on the local economic benefits of forest conservation and the potential role of forests in adaptation to climate change. In an agricultural settlement zone in the Brazilian Amazon, we find that the proportion of a property's drainage area with mature forest cover is significantly positively related to the milk output of that property. We determine that this is due to the effect of forest in small drainage areas, and that effect is largest when water is either scarce (in the dry season of a drought year) or excessive (in the wet season of a flood year). In large drainage areas, or in years of normal rainfall, upstream forest cover does not affect downstream dairy production.

Estimation results for models of productivity suggest that the effect of upstream forest on production operates through increases in both the stocking density of pasture and milk production per cow, and thus milk production per hectare of pasture.

While we find robust evidence of a positive relationship between downstream productivity and upstream forest in small drainage areas, we do not observe the specific hydrological mechanisms underlying this relationship. The relationship may be due to the combined effects of quantity and quality of the water, which we are not able to disentangle. When forests are converted to pasture, ponds and reservoirs are often constructed, very likely affecting the quantity of water available downstream in the dry season. In the wet season, forests can reduce flood peaks and inundated area, particularly in small drainages (Rodriguez et al., 2010), which could increase production in relatively wet years. Forests are known to maintain water quality, including higher dissolved oxygen and lower suspended sediment concentrations(de Mello et al., 2018), and water quality could in turn influence ruminant digestion and milk production (Gharibi et al., 2012). Our reduced-form evidence on the positive effect of upstream forest on downstream production should motivate further investigation of the intermediate linkages between forest cover, water quality and quantity, and milk production.

Our study provides estimates of the economic benefits of local watershed services of forests. This is important because tropical forest conservation policy is often treated as a trade-off between global environmental benefits and local economic (or human welfare) costs. Based on our estimates for properties fed by small drainages in flood or drought years, the value of watershed services generated by a marginal hectare of forest is 2010 PPP US$6.52–16.22/ha/year/property.[14] If we aggregate the downstream properties affected by deforestation of a single hectare in a small drainage area, the annual value of local forest watershed services is about 2010 PPP US$ 19.55–48.67/ha. Previous studies of watershed services have estimated annual values ranging from 2010 PPP US$ 5/ha to US$ 1160/ha across different sites, countries and regions (Ninan and Inoue, 2013). Our estimates thus fall within the broad range of estimates in the literature.

This type of evidence on the existence and local economic value of forest watershed services could encourage policy-makers to take the benefits of standing forest and the externalities of deforestation into account in land use policies. Further, farmers whose productivity is sensitive to up-stream forest cover could become a local constituency for forest conservation. In both cases, our evidence suggests that attention should be focused on small drainages, where forest cover is more likely to significantly affect downstream production. Alternatively, governments and farmers may choose to promote production systems less sensitive to up-stream forest cover in an effort to increase resilience to on-going deforestation and climate change.

To place our results in context, it is important to note that the estimated value of forest watershed services for downstream dairy production is small relative to the opportunity cost of retaining the forest (2010 PPP US$ 145.37/ha/year, Mullan et al., 2018; 2010 PPP US $30–11,971/family/year, Ickowitz et al., 2017). This is consistent with the lack of any systematic difference in management of drainages vs. other areas of farms, which suggests that farmers do not value (or are not aware) of forest watershed services. However, the small estimated value

[14] The estimates are based on the results of upstream forest off farm lot.

may also be partly a function of our choice to focus exclusively on the dominant local agricultural activity, milk production, which may be less sensitive than crops to changes in water availability. Further, market values do not accurately capture the full costs and benefits of clearing forest. Watershed services are just one of a suite of services provided by forests, and local watershed services are just one way that forests affect the hydrological system (Lima et al., 2014; De Sales et al., 2020).

Rainfall is becoming more variable in the Amazon Basin, likely due to both global climate change and regional deforestation (Zeng et al., 2008; Marengo and Espinoza, 2016). The increased frequency of historically rare droughts in the region has raised concerns about impacts on fluvial transportation, forest flammability, and regional carbon balance with feedbacks to climate change (Malhi et al., 2008; Phillips et al., 2009; Lewis et al., 2011; Marengo et al., 2013). Agricultural productivity is also affected. This increases the importance of strategies to enhance the resilience of family farmers such as the dairy producers in our study region. Maintaining upstream forests could offer a nature-based solution (Ruangpan et al., 2020). Although the average value of local forest watershed services is small, conserving forest cover in the drainages that supply family farms could enhance their resilience in the face of precipitation extremes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

For comparison, we estimate two alternative specifications: interacting forest cover in the drainage area only with drainage group, and interacting forest cover in the drainage area with dummy variables for year, while controlling for drainage area. In the first specification (Table A1, panel A in Appendix A), the significant positive effect of forest on milk production is still observed for farms fed by small drainages. In the second specification (Table A1, panel B in Appendix A), upstream forest has a significant positive effect on milk production only in 2000. In the driest year, 2005, upstream forest still has a significant

Table A1
Alternative specifications.

	Total milk production		Cow/pasture		Milk/cow, dry		Milk/cow, wet		Milk/pasture,dry		Milk/pasture,wet	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
A. drainage group* forest off lot forest off lot by drainage group												
S	0.193**	0.175*	0.104***	0.095**	0.157*	0.157*	0.183**	0.175**	0.153**	0.148**	0.177**	0.165**
	(0.092)	(0.093)	(0.036)	(0.04)	(0.078)	(0.083)	(0.079)	(0.082)	(0.071)	(0.076)	(0.072)	(0.074)
L	-0.152	-0.172	-0.056	-0.069	-0.158	-0.156	-0.15	-0.136	-0.116	-0.132	-0.115	-0.12
	(0.274)	(0.228)	(0.107)	(0.09)	(0.232)	(0.195)	(0.236)	(0.2)	(0.211)	(0.175)	(0.214)	(0.181)
B. year*forest off lot forest off lot by year												
1996	0.071	0.101	0.084	0.095*	-0.004	0.037	0.043	0.059	0.038	0.073	0.085	0.097
	(0.168)	(0.111)	(0.066)	(0.05)	(0.145)	(0.103)	(0.147)	(0.103)	(0.13)	(0.089)	(0.133)	(0.09)
2000	0.396***	0.399**	0.167***	0.164**	0.297***	0.310**	0.353***	0.360**	0.274***	0.276**	0.325***	0.322**
	(0.134)	(0.176)	(0.053)	(0.071)	(0.114)	(0.147)	(0.116)	(0.152)	(0.103)	(0.134)	(0.105)	(0.139)
2005	0.156	0.131	0.078*	0.065	0.183**	0.178*	0.128	0.116	0.178**	0.169*	0.13	0.116
	(0.107)	(0.112)	(0.043)	(0.046)	(0.09)	(0.107)	(0.092)	(0.096)	(0.082)	(0.098)	(0.084)	(0.088)
2009	0.130	0.110	0.091**	0.079	0.062	0.068	0.154*	0.146	0.065	0.066	0.148*	0.135
	(0.107)	(0.122)	(0.042)	(0.052)	(0.092)	(0.103)	(0.093)	(0.106)	(0.083)	(0.094)	(0.085)	(0.096)

Notes: The cells report the average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable, with standard errors in parentheses.
The first row indicates the six dependent variables.
Regressions include the same controls as in the Table 2. The IHS transformation was applied to all dependent variables and continuous independent variables with skewed distributions.
"S" represents small drainage, and "L" represents large drainage.

positive effect on the stocking rate and on productivity in the dry season.

Table B1
Marginal effects of forest in the whole drainage area: no interaction terms.

	Total milk production		**Cow/pasture**		**Milk/cow, dry**		**Milk/cow, wet**		**Milk/pasture,dry**		**Milk/pasture,wet**	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
Forest	0.108	0.100	0.097**	0.090**	0.096	0.113	0.142	0.144	0.093	0.107	0.137	0.137
	(0.114)	(0.108)	(0.045)	(0.045)	(0.097)	(0.099)	(0.098)	(0.096)	(0.088)	(0.089)	(0.090)	(0.086)
Year 2000	-1.707***	-1.707***	-0.420*	-0.411*	-1.418***	-1.415***	-1.578***	-1.578***	-1.187***	-1.194***	-1.202***	-1.203***
	(0.550)	(0.565)	(0.219)	(0.220)	(0.465)	(0.471)	(0.419)	(0.450)	(0.416)	(0.424)	(0.378)	(0.406)
Year 2005	-1.931***	-1.812***	0.004	0.0421	-2.274***	-2.188***	-1.957***	-1.916***	-1.800***	-1.722***	-1.478***	-1.460***
	(0.574)	(0.580)	(0.227)	(0.233)	(0.485)	(0.494)	(0.528)	(0.521)	(0.438)	(0.449)	(0.478)	(0.478)
Year 2009	-2.575***	-2.433***	-0.705**	-0.649**	-1.898***	-1.777***	-2.197***	-2.109***	-1.757***	-1.644***	-1.883***	-1.811***
	(0.740)	(0.735)	(0.292)	(0.290)	(0.626)	(0.636)	(0.577)	(0.585)	(0.566)	(0.572)	(0.524)	(0.528)
Drainage area	-0.194	-0.160	-0.141*	-0.122*	-0.152	-0.156	-0.240	-0.230	-0.124	-0.125	-0.199	-0.187
	(0.202)	(0.179)	(0.079)	(0.072)	(0.171)	(0.157)	(0.174)	(0.158)	(0.157)	(0.141)	(0.159)	(0.142)
Water access	0.672	0.610	0.301*	0.281*	0.546	0.523*	0.580	0.530*	0.542	0.526*	0.552	0.514*
	(0.464)	(0.375)	(0.180)	(0.143)	(0.392)	(0.312)	(0.397)	(0.320)	(0.361)	(0.280)	(0.364)	(0.288)
Milk price	4.366	4.392	2.210	2.088*	2.777	2.748	-0.297	0.574	4.093	4.162*	0.826	1.934
	(3.477)	(2.799)	(1.387)	(1.200)	(2.942)	(2.370)	(3.402)	(2.626)	(2.634)	(2.183)	(3.074)	(2.378)
Distance	0.027	-0.062	0.183	0.132	-0.093	-0.155	-0.002	-0.061	0.023	-0.055	0.085	0.015
	(0.394)	(0.364)	(0.153)	(0.145)	(0.333)	(0.304)	(0.337)	(0.312)	(0.307)	(0.272)	(0.309)	(0.280)
Household age	0.052***	0.049***	0.019***	0.018***	0.037***	0.032**	0.038***	0.034**	0.035***	0.032***	0.037***	0.034***
	(0.014)	(0.016)	(0.005)	(0.006)	(0.012)	(0.013)	(0.012)	(0.013)	(0.011)	(0.012)	(0.011)	(0.012)
Household edu	0.013	0.010	-0.003	0.006	-0.033	-0.044	-0.003	-0.008	-0.014	-0.017	0.011	0.015
	(0.080)	(0.086)	(0.032)	(0.034)	(0.068)	(0.072)	(0.069)	(0.074)	(0.061)	(0.065)	(0.063)	(0.067)
Household size	0.098***	0.130***	0.045***	0.057***	0.077**	0.104***	0.081**	0.110***	0.065**	0.093***	0.071**	0.099***
	(0.036)	(0.041)	(0.014)	(0.015)	(0.031)	(0.034)	(0.032)	(0.035)	(0.028)	(0.031)	(0.029)	(0.032)
Soil	0.512	0.554	0.147	0.205	0.273	0.303	0.459	0.490	0.263	0.340	0.461	0.540
	(1.434)	(0.897)	(0.559)	(0.388)	(1.209)	(0.699)	(1.230)	(0.747)	(1.115)	(0.630)	(1.126)	(0.678)
Slope	0.028	0.085	0.031	0.097	-0.165	-0.096	-0.170	-0.162	0.039	0.132	0.059	0.091
	(0.661)	(0.583)	(0.257)	(0.226)	(0.558)	(0.485)	(0.567)	(0.507)	(0.515)	(0.443)	(0.519)	(0.461)
Lot size	-1.208**	-1.086**	-0.733***	-0.713***	-0.692	-0.647	-1.494***	-1.414***	-0.924**	-0.888**	-1.643***	-1.576***
	(0.507)	(0.477)	(0.196)	(0.187)	(0.430)	(0.435)	(0.435)	(0.416)	(0.395)	(0.398)	(0.397)	(0.378)
Lot age	0.115***	0.112***	0.018	0.016	0.070**	0.070**	0.104***	0.104***	0.065**	0.063**	0.095***	0.094***
	(0.035)	(0.034)	(0.014)	(0.013)	(0.030)	(0.031)	(0.030)	(0.030)	(0.027)	(0.029)	(0.028)	(0.028)
Municipality (spatial) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	933	933	933	933	933	933	933	933	933	933	933	933

Notes: The cells report the average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable, with standard errors in parentheses.
The first row indicates the six dependent variables.
The IHS transformation was applied to all dependent variables and continuous independent variables with skewed distributions: forest in the whole drainage; drainage area; distance; slope; and lot size.
In the regression of lHS(total milk production) and lHS(cow/pasture), "milk price" represent the average values for dry and rainy seasons. In the regression of lHS (milk/cow, dry) and IHS(milk/pasture, dry), "milk price" represents values in the dry season. In the regression of lHS(milk/cow, wet) and IHS(milk/pasture, wet), "milk price" represents values in the wet season.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table B2
Marginal effects of forest in the whole drainage area: three-way interactions.

	Total milk production		Cow/pasture		Milk/cow, dry		Milk/cow, wet		Milk/pasture,dry		Milk/pasture,wet	
	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit	RE Tobit	Pooled Tobit
Forest by year and drainage group												
1996 S	-0.173	-0.089	-0.029	0.000	-0.151	-0.023	-0.066	-0.001	-0.156	-0.036	-0.072	-0.011
	(0.317)	(0.206)	(0.125)	(0.087)	(0.275)	(0.149)	(0.281)	(0.168)	(0.244)	(0.143)	(0.252)	(0.161)
1996 L	-0.510	-0.527	-0.200	-0.197	-0.422	-0.415	-0.332	-0.337	-0.378	-0.383	-0.307	-0.322
	(0.427)	(0.340)	(0.166)	(0.144)	(0.367)	(0.291)	(0.372)	(0.297)	(0.330)	(0.260)	(0.336)	(0.267)
2000 S	-0.084	-0.113	0.043	0.021	-0.077	-0.093	-0.062	-0.071	-0.052	-0.081	-0.042	-0.062
	(0.214)	(0.197)	(0.089)	(0.091)	(0.183)	(0.172)	(0.187)	(0.184)	(0.164)	(0.149)	(0.169)	(0.161)
2000 L	-0.190	-0.193	-0.139	-0.130	-0.167	-0.149	-0.050	-0.037	-0.157	-0.149	-0.065	-0.061
	(0.396)	(0.398)	(0.154)	(0.150)	(0.338)	(0.329)	(0.341)	(0.338)	(0.306)	(0.298)	(0.309)	(0.307)
2005 S	0.226	0.206	0.187***	0.178**	0.224*	0.224	0.188	0.184	0.235*	0.231	0.209	0.204
	(0.170)	(0.176)	(0.069)	(0.073)	(0.140	(0.193)	(0.148)	(0.158)	(0.128)	(0.174)	(0.135)	(0.143)
2005 L	-0.383	-0.386	-0.169	-0.171	-0.263	-0.251	-0.333	-0.316	-0.251	-0.246	-0.320	-0.309
	(0.324)	(0.272)	(0.129)	(0.115)	(0.270)	(0.227)	(0.277)	(0.233)	(0.247)	(0.211)	(0.253)	(0.217)
2009 S	0.287*	0.281	0.142**	0.137*	0.221*	0.244*	0.337**	0.338**	0.198*	0.221*	0.303**	0.304**
	(0.152)	(0.175)	(0.060)	(0.078)	(0.131)	(0.148)	(0.132)	(0.155)	(0.119)	(0.133)	(0.120)	(0.138)
2009 L	-0.373	-0.341	-0.079	-0.073	-0.324	-0.284	-0.284	-0.245	-0.269	-0.236	-0.239	-0.209
	(0.327)	(0.310)	(0.127)	(0.123)	(0.278)	(0.260)	(0.283)	(0.269)	(0.252)	(0.233)	(0.256)	(0.243)

Notes: The cells report the average marginal effects (the average of individual marginal effects) on the observed (censored) dependent variable, with standard errors in parentheses. Regressions include the same controls as in the Table 2.
The IHS transformation was applied to all dependent variables and continuous independent variables with skewed distributions.
"S" represents small drainage, and "L" represents large drainage.
"***", "**", "*", indicate significance at the 1%, 5%, and 10% levels.

Table B3
Durbin Wu-Hausman test for endogeneity of forest cover in drainage area on lot.

	Total milk production	Cow/ pasture	Milk/cow, dry	Milk/cow, wet	Milk/pasture, dry	Milk/pasture, wet	Milk revenue, dry	Milk revenue, wet	Total milk revenue
χ^2 statistics	1.67	2.40	0.98	1.82	1.04	2.12	0.51	4.14	1.73
p-value	0.197	0.121	0.322	0.178	0.308	0.145	0.474	0.042	0.188

Notes: The regressions performed are based on RE Tobit model.
The first row indicates the nine regressions with the nine different dependent variables.

Appendix B

For comparison, we estimate the same specifications with forest in the whole drainage area.

Appendix C. Supplementary data

Supplemental information to this article can be found online at https://doi.org/10.1016/j.ecolecon.2021.106965.

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