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Shifting cultivation, forest fallow, and externalities in ecosystem services: Evidence from the Eastern Amazon

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ABSTRACT

This study examines the value of fallow ecosystem services in shifting cultivation, including hydrological externalities that may affect other farms. Using farm-level survey data from the Brazilian Amazon, I estimate a production function to assess the value of forest fallow and test whether it provides local externalities to agricultural production. Soil quality controls, instrumental variables, and spatial econometric approaches help address endogeneity issues. I use GIS data on external forest cover at the farm level and model the hydrological externality as an upstream-to-downstream process. The estimated parameters indicate that fallow contributes significantly to productivity both on farm and downstream. In addition, most farms allocate sufficient land to fallow, accounting for both the value of hydrological spillovers and the opportunity cost of land left out of cultivation. These results suggest that farming communities may have some self-interest in preserving forest cover locally—a finding that may bolster policy efforts aimed at conserving tropical forests for their global public goods.

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1. Introduction

With tropical deforestation a major contributor to greenhouse gas emissions and biodiversity loss, the land-use decisions of small-scale farmers at the forest margins have important implications for the global environment. Proposals such as Payments for Ecosystem Services [1] and Reduced Emissions from Deforestation and Forest Degradation, or REDD [2], focus on compensating local communities to preserve virgin forests and their associated ecosystem services.

Under a shifting cultivation or slash-and-burn farming system, long fallow periods can allow secondary forest to regenerate, providing similar levels of carbon sequestration and other ecological functions as virgin forests [3]. Farmers' incentives for maintaining forest fallow depend on the market and non-market services it provides to them. Farmers who maintain large amounts of forest fallow as an agricultural input do so not because of the global climate benefits, but because fallow improves agricultural productivity at low cost. Where land is abundant and other inputs are scarce, long fallow periods can be a cost-effective way to restore land for future use, providing on-site benefits such as soil regeneration, erosion prevention, weed control, and harvestable products. Fallow may also provide local off-site services, such as hydrological regulation that moderates the flow of water in the soil.

Understanding how farmers in key eco-regions value and manage forests in agricultural systems can help in predicting future trends in tropical deforestation and designing policies to protect global public goods provided by forests. Improved information about the magnitude of secondary forests' contribution to agricultural productivity will be increasingly important as population and economic pressures spur many of the estimated 300 million [4] shifting cultivators

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world-wide to shorten fallow periods, adopt new technologies, and intensify cultivation. But economic studies accurately estimating the value of forest ecosystem services are sparse. Valuing the net benefits of forest cover to local populations could help justify conservation efforts with global importance [5]. The Millennium Ecosystem Assessment [6] has identified lack of information about the value of non-market ecosystem services—particularly regulating services such as hydrological functions—as a major knowledge gap hampering informed decision-making on ecosystem management.

This paper takes up this challenge by estimating the value of fallow ecosystem services in shifting cultivation in one region of the Brazilian Amazon. The analysis uses cross-sectional farm survey data from the Bragantina region of the Eastern Amazon to assess the value of forest fallow to farmers and test whether it provides economically significant local externalities that may justify forest conservation from a local perspective. I estimate a production function to determine the contributions of on-farm and off-farm forest fallow to agricultural income. Soil quality controls, instrumental variables, and spatial econometric approaches help address issues of endogeneity and variation in unobservable factors over space. I use geographic information on the location of farms to obtain data on external forest fallow and to model the hydrological externality as an upstream-to-downstream process.

A related contribution of this study is the separation of on-farm soil quality benefits and local hydrological spillovers, which is made possible by private land tenure in the study region. In many contexts world-wide, fallow is a common property resource prone to overexploitation in the absence of community controls [7–9]. The few previous studies estimating the value of fallow in agricultural production have focused on open access systems, making it more difficult to disentangle on-farm and off-site effects.

Estimation of these separate effects also allows me to investigate whether farmers manage fallow efficiently to maximize agricultural income, accounting for the opportunity costs of leaving land out of production. I test empirically whether farmers in the study region manage fallow efficiently from either a household or a community-level perspective. If fallow ecosystem services are limited to improving on-site productivity, then a private land ownership regime could foster improved outcomes compared with common property management. However, if local externalities are economically significant, then inefficiencies could arise even under private land tenure. Correcting these inefficiencies could boost downstream farm income while providing incidental carbon sequestration. Thus, whether fallow biomass provides externalities is an empirical question with important implications for tropical forest policy.

2. Fallow as a production input in shifting cultivation

Fallow refers to land that is idled as part of a shifting cultivation system after being planted with annual or short-term perennial crops, accumulating nutrient-rich biomass that can serve as fertilizer when the land is brought back to cultivation. Some authors distinguish among different categories of fallow based on age and biomass density, with forest fallow representing more mature regrowth than grass fallow or bush fallow [10]. In some areas of the humid tropics, tree cover rapidly regenerates on fallow land, leading to considerable secondary forest cover if fallow periods are sufficiently long. Fallowing restores plots for future cultivation by drawing soil nutrients and water to the surface, raising soil pH, minimizing surface erosion, and suppressing weeds [10–15]. In addition to these ecosystem services, forest fallow also serves as a source of harvestable forest products such as firewood.

Agroecological studies also suggest that forest fallow provides beneficial spillovers that can enhance agricultural productivity on nearby farms, particularly through the hydrological cycle. Tree cover lessens peak flows and surface runoff due to increased infiltration and evapotranspiration of soil water [16,17]. Recent studies examining the impact of afforestation in Latin American tropical grassland ecosystems found that tree cover caused statistically significant reductions in soil water flow, which became more pronounced with the age of the forest stand [18,19]. Reduced baseflow can be detrimental in dry regions but advantageous in wet areas by lessening floods, waterlogging, and leaching, which may benefit agricultural activities downstream. Larger changes in baseflow typically occur in areas with flatter slopes and less-rocky soils because water is less likely to escape the soil [18]. Improved infiltration may also lead to higher dry season baseflow in some cases [17]. Forest stands can enhance nearby farms' productivity through crop pollination [20,21] and tree seed availability [25].

Few studies have estimated the value of fallow biomass and forest cover in agricultural production, and none have separately estimated the value of on- and off-farm services in the same agroecosystem. López [7,8] showed that village-level fallow biomass (capturing both on-farm soil quality and external hydrological benefits) contributed significantly to agricultural profitability in Ghana and Côte d'Ivoire. Goldstein and Udry [9] also showed the importance of fallow for on-farm soil quality restoration in Ghana but did not address off-site benefits. Research in Ruteng National Park, Indonesia, found that sub-watershed-level off-farm forest cover provided beneficial hydrological services (in this case, drought mitigation) to small-scale agricultural production [22,23]. This study adds to the literature by isolating the value of fallow externalities from on-farm services at the household level in the Brazilian Amazon, an eco-region with global importance due to its vast biodiversity and carbon stocks.

3. Study region and data

The Bragantina region offers a compelling case study as a region with over a century of agricultural settlement, where shifting cultivation persists as the principal means of livelihood. Despite integration into regional markets through railways and roads, agro-processing, and government programs to encourage agricultural intensification, shifting cultivation remains a dominant land-use practice in the region.

Most households in Bragantina are considered smallholders by Brazilian standards, with landholdings under 100 ha. Family labor and manual land clearing predominate, though hired labor and mechanized equipment are also used for labor-intensive tasks like land preparation, weeding, and harvesting. A typical 1–2 year cropping sequence includes maize, upland rice, and cowpea, with cassava grown as the final crop while fallow vegetation reestablishes [12]. These annual crops are used for home consumption and sale to regional markets. Many smallholders also cultivate perennials like black pepper, passion fruit, oranges, and coconut. Harvesting products like firewood, honey, and fruits from forest fallow is another common activity.[1]

While virtually all of the native tropical forest in Bragantina has been cleared over the decades, up to 75% of the land area remains under secondary forest in some municipalities as a result of the shifting cultivation system [24]. Root systems remain intact after manual land clearing, fostering rapid vegetative regeneration of tree species during initial fallow years [3]. Fallow in the study area is composed of a mosaic of vegetation in a variety of stages of regrowth, ranging from grasses and shrubs to closed-canopy tree cover. Typical fallow lengths of 4–8 years result in tree cover reaching heights of 3–10 m [3,12,24,25]. Forest fallow in Bragantina exhibits many similarities with virgin forest, providing similar levels of nutrient accumulation and below-ground carbon sequestration, though less tree species diversity [3,25].

Soil is relatively homogenous in the region, though of poor quality. The region faces major challenges in improving agricultural productivity due to low-nutrient Oxisol, Spodosol, and Ultisol soils vulnerable to acidity and aluminum toxicity [12,25]. Experiments varying fertilizer treatments in Bragantina identified phosphorus and nitrogen as the major limiting factors in crop production and fallow biomass growth [26]. Slopes are relatively flat, minimizing the risk of water erosion but increasing the impact of tree cover on soil moisture. The climate is humid, receiving an average rainfall of 2400–2700 mm annually, with rainfall decreasing along a gradient from east to west. Rainfall is concentrated during the wet season from January to April, with an intense dry season from September to November. Although this study focused on dryland rather than floodplain farms, 37% of a small subsample of 25 of the surveyed farmers identified excess rains as a major source of risk, while another 26% pointed to drought as a predominant risk factor, indicating that hydrological moderation could be valuable to Bragantina farmers [27].

Data for the study were collected as part of the SHIFT (Studies on Human Impact on Forests and Floodplains in the Tropics) project, an initiative to study tropical livelihoods and ecosystem dynamics in Brazil. Three municipios out of the 14 that comprise Bragantina were chosen to capture regional variation in distance to commercial centers, agricultural intensification, and rainfall [28]. In late 2002, 271 households in 22 villages were randomly selected and surveyed. The survey gathered farm production, land use, and demographic data for the 2001–2002 growing season.

Comprehensive farm-level data on forest fallow for the entire region would be ideal to estimate the off-site flow of benefits, but such data are unavailable. I use the household survey data on land use among the sampled farms as one solution. Farmers reported the land area under fallow during the growing season, along with the area under cultivation and pasture, providing a reliable source of data on household-level fallow inputs. While the survey did not collect information on fallow biomass density, density is positively correlated with fallow area under steady state management.

As an additional data source, I turn to Geographic Information Systems (GIS) data on forest cover, using the MODIS Vegetation Continuous Fields (VCF) to construct an alternative measure of fallow. The VCF data consist of 25 ha resolution pixels created using 40 day composite satellite images from March 2001 to March 2002 [29].[2] Each pixel represents percent canopy cover, defined as the amount of sunlight blocked by trees over 5 m high, a height typically reached in the region after 5–10 years of fallow. GIS data are useful for this analysis because virtually all tree cover in the region of this height is fallow rather than virgin forest, though inaccuracies could result due to uncertainty in interpretation of land cover using satellite data.

I also use GIS flow direction data from the US Geological Survey [30] to determine where farms lie along a gradient from upstream to downstream in relation to one another. According to a flow direction map for the region, farms cluster into 11 groups defined by a common drainage area and flow direction. Each cluster includes at least one sampled community. Within each group, I assume each observation affects farms downstream and is affected by farms upstream. The US Geological Survey also provides slope data for the region at 1-km resolution.

4. Production function estimation

The dependent variable in the production function is the log of farm output value. Farm output includes a variety of crops and forest products, with different commodities aggregated using average output prices in the region. Although farms reserved some output for home consumption, market prices provide appropriate values for these commodities since 97% of sampled farmers sold at least some of their produce. I employ a Cobb–Douglas specification for technology. Output

[1] Farmers also engage in livestock production, though this activity is less common in Bragantina than either cropping or forest product collection.

[2] The 2001–02 VCF data provide the closest available estimates of forest cover during the 2001–2002 cropping season. Pixels are 25 ha—the same size as the median farm among surveyed farmers. The percent canopy cover approximates both the area and density of forest cover, since the share of land with 5-m tree cover is likely to be highly correlated with vegetation density.

is modeled as a function of cultivated land area, family and hired labor, fertilizer, pesticide use, on-farm fallow, and off-farm (upstream) fallow. Because farm and forest products are marketed goods, valuation of the fallow ecological services using a production function approach is straightforward and does not depend on detailed knowledge of the ecological mechanisms at work [31].

Farm i's agricultural revenue y_i can be represented as

$$\ln y_i = \beta_o + \beta_1 \ln \theta_i + \beta_2 W_1 \ln \overline{\theta} + \beta_3 \ln X_i + \beta_4 H_i + \varepsilon_i \tag{1}$$

where $\varepsilon_i = \lambda W_2 \varepsilon + u_i$. Farm i's fallow biomass is represented by θ_i, while $\overline{\theta}$ is a vector of all farms' fallow. Cultivated land area, family and hired labor, and fertilizer are represented by X_i, a vector of conventional inputs. Crop production is a function of all inputs, while forest product harvests are expected to be determined only by fallow inputs, family labor, and land quality.

The error term is given by ε_i, which includes a component that varies over space and a white noise term, u_i. A spatial error model accounts for the fact that unobserved factors may influence farmers' and their neighbors' land use decisions in similar ways, allowing for efficient estimation of the parameters. The strength of spatial correlation among the disturbances is represented by λ.

Spatial weighting matrices for off-farm fallow and the error term are represented by W_1 and W_2, respectively. W_1 is a row-normalized matrix that gives equal weight to neighbors upstream of each farm to capture the hydrological externalities of local forest fallow.[3] $W_1 \ln \overline{\theta}$ thus represents a weighted average of off-farm fallow area upstream of each observation.[4] I also refer to this term as a spatial lag of the fallow variable [32].

W_2 is a matrix of inverse distances between all sampled farms, reflecting correlation in unobserved factors expected to decline with distance, such as weather shocks. W_2 is not row normalized, as row normalization would imply that more isolated farms are affected by their neighbors' disturbances as much as farms with many neighbors in close proximity. The uniqueness of the two spatial weighting matrices is thus justified conceptually, and it allows for identification of spatial autoregressive parameters.[5] However, if spatial correlation among the disturbances or other non-stochastic factors follows the same pattern as the hypothesized hydrological externality, then these effects cannot be disentangled without further parameter restrictions.

I include household and farm characteristics in the vector H_i to control for observable aspects of management ability and land quality. Use of extension services helps control for farm management skills. A binary variable for perennial crop production controls for the higher prices perennial crops command in regional markets relative to annual crops.[6] Pesticide use is included as a binary variable, indicating whether chemical herbicides, fungicides, or insecticides were applied during the growing season. Land quality indicators include farmer-reported dummy variables for black clay and charcoal-enriched soil ("*massape*" and "*preta*," both favorable types) and GIS data on slope, which indicate the farm's vulnerability to erosion. While soil is fairly homogenous throughout the region and land is not steeply sloped, these variables help account for micro-level agroecological variation, an important consideration stressed by several empirical studies on Amazonian deforestation and farm income [33–35]. Table 1 reports the mean values for the variables used in the production function estimation.

The primary parameters of interest are coefficients of on-farm fallow and external fallow, which indicate their contribution to farm productivity. I tackle the hypothesis that local forest cover provides positive externalities to downstream farms by testing whether the coefficient of the spatially weighted upstream forest fallow variable is significantly greater than zero.

5. Fallow variable definitions

I use area under fallow during the cropping season as a proxy for fallow biomass. While fallow area does not directly measure biomass or capture the dynamic aspects of fallowing, larger fallow relative to cultivated area allows for more forest recovery time and higher peak biomass density.[7] The two alternative measures of off-farm fallow are (1) average 2002 area under forest fallow upstream of each farm, measured by the household survey data and using the spatial

[3] Estimation results do not qualitatively differ when upstream neighbors are weighted by inverse distance.

[4] Although row normalization is not appropriate in all spatial analyses, normalizing by the number of sampled farms in each farm's neighborhood is important in this case to avoid inferring that farms with more sampled neighbors have higher levels of nearby forest cover.

[5] As shown by Anselin [32], spatial lag and spatial error parameters are generally not identified without nonlinear restrictions when the two weighting matrices are the same.

[6] In a preliminary attempt to control for the potential endogeneity of producing perennial crops, I estimated a treatment effects model. I could not reject they hypothesis that the farm output and perennial production equations were independent (p=0.45), so I treat perennial production as exogenous in the regressions that follow. Perennial crops can be grown in soil conditions found throughout Bragantina. However, farmers facing higher rainfall, better access to extension services, and those less averse to price risks are more likely to produce perennials.

[7] When fallow management is in steady state equilibrium, fallow area has a direct relationship with biomass volume, though the relationship is still positive when the system is out of equilibrium [7]. The steady state assumption is plausible in the conditions of Bragantina, where agronomic practices and population density have remained similar for several decades, unlike much of the Brazilian Amazon. López [8] found similar output elasticities of fallow using biomass volume and fallow area as alternative measures in Ghana.

Table 1
Farm production variables.

	Mean (standard deviation)	Observations
Crop output value (R$[a])	5080.59 (11,972.60)	271
Forest product output value (R$)	666.94 (3206.31)	271
Cultivated area (ha)	3.75 (4.64)	270
Family labor (person-days)	112.47 (97.42)	271
No family labor used: 1=yes, 0=no	0.02 (0.15)	271
Hired labor (person-days)	52.94 (75.36)	271
No hired labor used: 1=yes, 0=no	0.17 (0.37)	271
Fertilizer (kg NPK)	389.90 (1525.69)	271
No fertilizer used: 1=yes, 0=no	0.29 (0.46)	271
Used pesticides: 1=yes, 0=no	0.46 (0.50)	271
Produce perennial crops: 1=yes, 0=no	0.46 (0.50)	271
Use extension services: 1=yes, 0=no	0.24 (0.43)	271
Slope (deg)	2.65 (2.54)	261
Black clay (*massape*) soil: 1=yes, 0=no	0.10 (0.30)	271
Charcoal enriched (*preta*) soil: 1=yes, 0=no	0.10 (0.31)	271
Community-level fertilizer price index (R$/kg)	0.93 (0.10)	271

[a] US$1=R$2.97, 2002 average.

Table 2
Fallow variables.

	Mean (standard deviation)	Observations
Farm size (ha)	40.73 (47.97)	271
On-farm fallow area (ha)	22.60 (28.97)	271
No on-farm fallow land: 1=yes, 0=no	0.14 (0.35)	271
Total off-farm (upstream) fallow area—survey data (ha)	367.15 (356.90)	236
No upstream fallow area: 1=yes, 0=no	0.03 (0.16)	236
Total off-farm (upstream) canopy cover—GIS data, 3 km radius (ha)	169.03 (62.37)	261
No upstream canopy cover: 1=yes, 0=no	0 (0.00)	261

weighting matrix W_1 to define which farms are considered neighbors[8] and (2) percent canopy cover within 3 km upstream of each farm, given by the VCF data.[9] Both approaches define the externality at the farm level, allowing for more variation in the off-farm forest cover variable compared with other studies that define the forest externality at the village or sub-watershed level (e.g., [7,8,22,23]). Table 2 summarizes the fallow variables.

6. Endogeneity and identification strategy

Potential endogeneity of the fallow variables is a concern in obtaining consistent parameter estimates, particularly if poor soil quality spurs farmers to fallow more land while depressing yields, biasing the on-farm fallow coefficient downward. Measurement error of the on-farm fallow area variable, which proxies for but does not exactly measure biomass, may cause attenuation bias, further lowering the elasticity estimates [36]. Measurement error is a particular concern in the specification with on-farm fallow area and off-farm GIS canopy cover. Since the two variables are correlated and GIS canopy cover may be a better proxy for biomass density than fallow area, mismeasurement of the on-farm variable could bias the coefficient of on-farm fallow downward and the coefficient of GIS canopy cover upward. The error term in the production equation thus encompasses not only white noise, but also measurement error, agroecological conditions, farmer intentions, and other factors unaccounted for in the data.

With these drawbacks in mind, I employ several strategies to consistently estimate the parameters of interest. As discussed above, I include three observed indicators of land quality. These controls, which are jointly significant in predicting output (p=0.01), help to minimize omitted variable bias. Soil quality variables are important predictors of fallowing, as shown in the first stage equation for the instrumental variable (IV) strategy (see the appendix); as expected, good quality black clay soil is negatively associated with fallowing, while steeper slopes are positively correlated with

[8] Those farms furthest upstream within a locality are assumed to affect all downstream farms; however, they have no neighbors among the sampled farms and so are excluded from the final crop value equation testing for externalities.

[9] The GIS data give upstream forest cover for all farms for which I have GIS coordinates. GIS coordinates are missing for 10 farms in the sample, which are excluded from the analysis. I cannot extract upstream forest cover within each drainage area individually for each farm using the GIS data, so I instead extract a wedge-shaped neighborhood upstream of each farm with a radius of 3 km. The survey- and GIS-derived variables are positively and significantly correlated (ρ=0.36).

fallowing. When the soil quality variables are excluded from the farm revenue regression, the on-farm fallow coefficient decreases by 2 percentage points and is no longer significant at the 10% level. This result confirms that if soil quality is completely omitted from the production equation, the fallow coefficient is biased downward due to its negative correlation with fallowing, but that the control variables help mitigate this concern. The potential downward bias on the on-farm fallow coefficient also suggests that a least-squares estimate can be interpreted as a lower bound on the elasticity.

I also test the endogeneity of the fallow variable using an IV approach. If the control variables are insufficient to address endogeneity of the fallowing decision, then OLS estimates of the production function will be inconsistent, while IV estimates will be consistent. Comparing OLS and IV estimates serves as a test for exogeneity of on-farm fallow. If the OLS estimates are consistent, they are preferred to the IV estimates because they are more efficient. I use three instruments for on-farm fallow: the log of farm size and dummy variables indicating formal land ownership and gender of the household head. Somewhat mechanically, farm size affects the amount of land available for fallowing and so is likely to be a strong predictor of fallow area. Farm size has no direct effect on output because cultivated land area is included directly in the production function, making total farm area unrelated to output value.

Households with formal land title and male household heads might also be expected to allocate more land to fallow due to the longer planning horizon that comes with higher tenure security. Goldstein and Udry [9] observed this pattern in Ghana, where women farmers and those with lower status in the community fallowed less because they were more likely to have their land appropriated by other community members. Although formal property rights are common in Bragantina, unlike in the communities studied by Goldstein and Udry, land ownership as opposed to rental or informal use rights likely increases the time horizon for land management decisions, making a long-term investment in fallowing more attractive. Gender could have a similar effect on land use decisions if female household heads are more likely to have fallow land appropriated by extended family members. The three instruments are strong predictors of on-farm fallow area, as indicated by a Shea's partial R^2 statistic of 0.46. As anticipated, all are positively associated with fallow area.[10]

Admittedly, these instruments are not ideal; none is truly exogenous to farm production, and there are plausible scenarios in which they might be correlated with output revenue.[11] To maintain a measure of confidence in the validity of the instruments, I test their exogeneity statistically by including each variable individually in the output equation while using the other two variables as the set of instruments. None of the three variables is statistically significant in predicting farm output (p=0.37 for log farm size, p=0.56 for land ownership, and p=0.48 for male household head). A Sargan overidentification test also indicates that the variables are jointly exogenous (p=0.65).

A Durbin–Wu–Hausman test could not reject exogeneity of on-farm fallow in the output equation (p=0.48). Thus, the least squares estimates are the preferred estimates, being both consistent and more efficient than the IV estimates. A spatial error model is also used to further improve efficiency. Modeling spatial correlation in the error terms based on distance between farms helps control for unobserved patterns in agroclimatic factors and farmer knowledge over space.

Although endogeneity of the upstream fallow variables is less of a concern, I also tested their exogeneity as a sensitivity check using the spatially lagged values of the log of farm size and farm ownership as instruments. The spatially lagged values of these characteristics affect neighbors' land allocation decisions and hence off-farm fallow but are uncorrelated with the residual of own-farm output because own-farm characteristics are controlled for directly in the production function. I use the same spatial weighting matrix to construct the instrumental variables as that used to construct the lagged fallow variables to ensure that the weighted average of neighbors' fallow is regressed on the characteristics of these same neighbors. The instruments are positively correlated with off-farm fallow, with Shea's partial R^2 statistics of 0.62 for the survey fallow variable equation and 0.06 for the GIS variable equation.[12] Durbin–Wu–Hausman tests indicate that the off-farm fallow variables are exogenous (p=0.58 and 0.55 for the GIS and survey variables, respectively).

7. Treatment of non-essential inputs

Use of the Cobb–Douglas specification implies that all inputs are used in positive quantities. However, some farmers in the sample use no fertilizer, hired labor, or fallow land, and a few have no upstream forest cover, as indicated by the household survey data fallow area. I do not employ the widely used strategy of adding a small shifter to the inputs before taking logs because parameter estimates tend to be highly sensitive to the value of the shifter [37]. Instead, I deal with non-essential inputs according to the approach outlined by Battese [38], adding dummy variables to indicate non-use of each input.[13] These dummy variables function as different intercepts for farmers who do not use particular inputs. While non-use of fallow or conventional inputs might be indicative of a different production system than that used by

[10] See the appendix for the first stage equation results.

[11] In particular, a reviewer noted that farm size could be negatively correlated with output if lower-quality land is cheaper, making larger farms more likely to have poor soil. Alternately, farm size could be positively correlated with output if it is an indicator of wealth, as could farm ownership. I cannot rule out any of these scenarios. Thus, the IV estimates represent an attempt to test exogeneity in the absence of a more rigorous experimental or quasi-experimental approach.

[12] See the appendix for details. The Sargan test for overidentification indicates that the instrumental variables as a group are uncorrelated with the residuals of the crop output equation (p=0.48 for the GIS and p=0.97 for the survey variables specifications). Although this IV validity test has low power, it supports the assertion that the instruments are uncorrelated with crop value.

[13] Battese represents a two-input Cobb–Douglas production technology using two equations, assuming that one input is used by all firms, and a second input is used by only some firms.

most farmers, data are insufficient to estimate separate production functions for these individuals. In addition, three farms produced no crops or forest products during the season and are excluded from the crop production regression.

8. Results

Table 3 presents four sets of estimates of the production function. Column (1) reports estimates from the spatial error model (SEM), including only on-farm fallow and not upstream fallow. Column (2) presents the SEM estimates instrumenting for on-farm fallow, again excluding upstream fallow. Columns (3) and (4) show estimates of the SEM including upstream as well as on-farm fallow, using the survey-reported off-farm fallow area and the GIS canopy cover variable, respectively. As stated above, the fallow variables can be considered exogenous, so all four sets of parameter estimates are consistent. All models have a satisfactory fit, as indicated by R^2 statistics of 0.52–0.56, and the coefficients largely have the expected signs across the different models. The spatial error correlation coefficient is not significantly different from zero in any of the specifications, indicating that unobserved variables varying with distance between farms have no systematic effect on output once inputs and observed farmer and soil characteristics are included.

Comparisons among the four models reveal that on-farm and upstream fallow are both important factors of production in Bragantina. The elasticity of on-farm fallow is significantly greater than zero across all models, varying from 0.10 to 0.16,

Table 3
Production function estimation—dependent variable: log farm output value.

	(1)	(2)	(3)	(4)
Log on-farm fallow area	0.114**	0.159*	0.135**	0.104*
	[0.057]	[0.084]	[0.056]	[0.059]
Log upstream fallow			0.355**	0.552***
			[0.144]	[0.205]
Log cultivated area	0.488***	0.481***	0.438***	0.478***
	[0.088]	[0.088]	[0.090]	[0.088]
Log family labor	0.05	0.05	0.054	−0.008
	[0.087]	[0.087]	[0.089]	[0.088]
Log hired labor	0.226***	0.218***	0.245***	0.270***
	[0.060]	[0.060]	[0.062]	[0.060]
Log chemical fertilizer	0.113*	0.116**	0.110*	0.153**
	[0.058]	[0.058]	[0.059]	[0.059]
Use pesticides (binary)	−0.202	−0.211	−0.06	−0.154
	[0.163]	[0.164]	[0.170]	[0.166]
Perennial producer (binary)	0.737***	0.734***	0.734***	0.738***
	[0.153]	[0.154]	[0.160]	[0.152]
Use extension services (binary)	0.256	0.266*	0.300*	0.292*
	[0.160]	[0.160]	[0.166]	[0.161]
Charcoal-enriched soil (binary)	0.337	0.352*	0.304	0.319
	[0.206]	[0.207]	[0.201]	[0.207]
Black clay soil (binary)	0.381*	0.387*	0.293	0.207
	[0.214]	[0.215]	[0.216]	[0.218]
Slope	−0.057**	−0.059**	−0.048*	0.071***
	[0.025]	[0.025]	[0.025]	[0.026]
No on-farm fallow (binary)	0.28	0.402	0.298	0.298
	[0.243]	[0.294]	[0.257]	[0.242]
No upstream fallow area (binary)			0.993*	
			[0.573]	
No family labor (binary)	0.763	0.747	0.743	0.529
	[0.641]	[0.641]	[0.634]	[0.643]
No hired labor (binary)	0.338	0.321	0.386	0.532**
	[0.258]	[0.259]	[0.267]	[0.263]
No fertilizer (binary)	−0.058	−0.063	−0.141	0.043
	[0.287]	[0.287]	[0.302]	[0.298]
Constant	4.881***	4.747***	3.808***	2.380**
	[0.598]	[0.605]	[0.665]	[1.021]
Spatial error correlation coefficient λ	−0.114	−0.126	−0.111	−0.094
	[0.108]	[0.110]	[0.126]	[0.167]
Observations	268	268	234	258
R^2	0.52	0.52	0.56	0.54
Log likelihood	−380.36	−380.57	−319.75	−362.03

Standard errors in brackets; all regressions estimated in Stata 8.

* Significant at 10%.

** Significant at 5%.

*** Significant at 1%.

suggesting that own-fallow land makes a substantial contribution to crop and forest product revenue. It is particularly noteworthy that the non-IV estimates are positive and significant, since they represent a lower bound on the elasticity due to the potential for downward bias.

The elasticity estimates are similar to those from other econometric and agronomic studies. For instance, López [7,8] found the village-level fallow biomass factor share to vary between 0.15 and 0.2 in Ghana and Cote d'Ivoire. Mendoza [28] used the same data set as this study to estimate the contribution of fallow length to cassava profits, finding an output elasticity of 0.22. An Altamira, Pará, field study found the elasticity of maize yields with respect to fallow age to be 0.33 [39]. An agronomic study from Bragantina showed rice yields to improve by 10–44% as fallow age increased from 4 to 10 years, corresponding to a fallow elasticity of 0.07–0.29, with the lower elasticities found on fields to which fertilizer was applied [24]. The wide use of fertilizer by sampled farms may help explain why the elasticities estimated here fall in the lower range of previous studies.

The estimated elasticity of off-farm fallow in farm production is positive and significantly different from zero in both models (3) and (4), providing evidence that upstream forest fallow improves productivity for downstream farms, though the magnitude of the estimate varies based on the fallow variable used. Model (3), which uses survey-reported fallow area as the measure of upstream fallow, shows an elasticity of 0.36. The effect is similar to the results from the Ruteng National Park, Indonesia, study, where a 10% increase in soil moisture due to afforestation was associated with a 2–3% boost in farm profits [23]. In model (4), which employs the GIS canopy cover variable to measure off-site fallow, the elasticity jumps to 0.55. This high coefficient could result from off-farm canopy cover proxying for on-farm biomass density, which is not completely reflected by the on-farm fallow area variable.

The positive elasticities of on-farm and upstream fallow demonstrate the importance of forest fallow to farms in Bragantina in providing both consumable products and ecological support services. These findings support the hypothesis that upstream forest fallow provides flows of economically significant ecological services to farms in Bragantina. They suggest that off-site hydrological regulation may be important even in low and moderately sloped regions with porous soils. These hydrological support services may justify continued allocation of land to forest fallow in the future, even if farms increasingly substitute chemical fertilizer for fallow-based soil nutrients.

The large magnitude of the upstream fallow elasticity estimate, which exceeds the on-farm fallow elasticity, is surprising. One reason why the upstream coefficient estimate seems high relative to the on-farm coefficient is because the total area of fallow land upstream of each farm is much larger than the fallow area on any individual farm (Table 2). When expressed as an elasticity, the impact of upstream fallow seems high because a 1% change in upstream fallow area represents a much bigger absolute change in fallow than a 1% change in fallow on a single farm. However, the relative impacts of on-farm and upstream fallow on output look different when expressed on a per-hectare basis. Dividing by average on-farm or upstream fallow area to express the respective elasticity estimates in terms of per-hectare impacts reveals that a 1 ha increase in on-farm fallow boosts farm production by about 0.5–0.7%. A 1 ha increase in upstream fallow improves production by 0.1–0.3%, depending on the model used. Thus, on a per-hectare basis, on-farm fallow is indeed the more important input, by a factor of 2–7.

Additional explanations for why the upstream fallow coefficient is high relative to the on-farm coefficient include downward bias of the on-farm fallow coefficient and upward bias of the GIS fallow coefficient due to measurement error in the on-farm variable, and the possibility that non-stochastic factors correlated with forest cover other than hydrological externalities affect downstream farm production. While the hydrological externality effect cannot be isolated if other factors lead to a correlation between off-farm land use and on-farm output, the positive and significant coefficient provides support for the hypothesis that farms benefit from forest cover upstream.

As another verification that forest cover provides hydrological externalities, I also estimate models (3) and (4) including downstream forest cover as an additional regressor. If forest cover provides positive hydrological externalities, then upstream forest cover will affect production but downstream forest cover will not. Across both models, downstream forest cover has no significant effect on output value, in contrast with upstream forest cover. In fact, the coefficient on downstream forest cover is negative in both models. These findings support the contention that forest cover improves farm output by regulating floods and soil moisture, and that other non-hydrological services such as crop pollination do not drive the results. These results are available from the author.

Elasticity estimates for the conventional inputs are largely positive and significantly different from zero across all four specifications. Cultivated area makes the most substantial contribution to output, with an elasticity of 0.44–0.49. Hired labor and fertilizer are also important, supplying 22–27% and 11–15% of output, respectively. Production of perennial crops raises output value considerably, as does use of extension services. Pesticide use is associated with lower output, possibly because it indicates pest infestation, while a more intensified production system is already controlled for by the fertilizer and perennial production variables.[14] Agroecological variables are also important—black clay and charcoal-enriched soils boost output and steeper slopes dampen it. Farms with no upstream fallow or hired labor garner higher revenues, as indicated by the coefficients of the dummy variables for non-use of each input.

[14] Indeed, pesticide use is significantly correlated with both perennial production and fertilizer use (ρ=0.44 and 0.48, respectively).

Table 4
Robust regression fallow coefficient estimates.

	Model (1)	Model (2)	Model (3)	Model (4)
On-farm fallow	0.140**	0.147**	0.162***	0.135**
	[0.058]	[0.061]	[0.057]	[0.060]
Upstream fallow			0.219**	0.457**
			[0.105]	[0.210]

I also estimated each of the four models using robust regression to ensure that the estimated elasticities of on- and off-farm fallow are stable in the presence of outliers.[15] Table 4 presents the on-farm and upstream fallow coefficient estimates from these regressions. When the impact of influential observations is minimized, the range of on-farm fallow coefficient estimates narrows to 0.14–0.16 but is generally similar to the estimates in Table 3. The upstream fallow coefficients are lower (than those in Table 3), though still significantly greater than zero, suggesting that the seemingly high relative impact of upstream compared with on-farm fallow discussed above might be driven by a few outliers.

9. Land allocation efficiency

While fallow provides important ecological services in shifting cultivation, it can be a costly investment when the opportunity costs of land and labor are considered. Land must remain out of cultivation for years at a time to ensure sustainability, and land clearing requires large investments of labor. The total returns to fallowing thus depend on the relative contributions of fallow and cultivated land to farm income once all costs are considered.

The estimated income elasticities of cultivated area, on-farm fallow, and upstream fallow can be used to determine whether farmers allocate land between cultivation and fallow efficiently. Farmers manage land efficiently if they balance the marginal contribution of cultivated area to income with the marginal value of the lost fallow services to farm production. I calculate the impact of a 1 ha increase in cultivated area on total community profits—not only those of the individual farm, but also the profits of all farms downstream.[16]

Under efficient allocation of land between cultivation and fallow, the marginal benefits of cultivated land minus the marginal costs in terms of land clearing, foregone soil quality, forest products, and positive externalities to other farms should equal zero. If it is significantly greater (less) than zero at the 1% level, the farm is considered to be over-(under-) fallowing. I test whether sampled farmers managed land efficiently, allocated too much land to fallow, or allocated too little according to each of the four sets of parameter estimates in Table 3.

This test reflects efficient land management accounting for all fallow services, including local externalities. In the absence of centralized or coordinated fallow management, however, farmers have no incentive to weigh foregone externalities as a cost. If farmers maximize individual profits, they do not consider the value of fallow for their downstream neighbors. Thus, I also test whether surveyed farmers allocate land to maximize individual rather than community profits.

Table 5 presents the results on land allocation efficiency, assuming a range of interest rates.[17] The first two columns present the results from models (1) and (2) of the production function, which include only on-farm fallow. Because they do not account for the externality effect, they test whether land allocation is individually profit-maximizing. The second two columns include the value of the upstream externality, as estimated in models (3) and (4), and can be interpreted as testing community profit maximization.

The results suggest that the externality effect is an important consideration when evaluating whether land management is optimal. Columns 1 and 2 indicate that when the externality is not included, around half or fewer of the farmers allocate land at individual profit-maximizing levels (20–52%, depending on the model and interest rate). Perhaps surprisingly, a substantial number of farmers (47–79%) devote more land to fallow than would maximize individual profits. Assuming a 10% interest rate and the model (1) coefficients, the average farmer forgoes R$574 in revenue by failing to expand cultivation to the individually optimal level.

Columns 3 and 4 suggest, however, that when the value of downstream hydrological services is included, only 9–34% of farmers over-fallow. Rather, land allocation appears to maximize community-level profits, since optimal land allocation cannot be rejected for a clear majority of farmers (63–89%). Few farmers seem to devote too little land to fallow (4% or fewer) under all four models. Thus, farmers appear to over-fallow from the private perspective, but the behavior is optimal once beneficial spillovers are taken into account. Regardless of interest rate, community-level profits would not increase by

[15] I use the Stata 8 robust regression estimator, which minimizes the influence of high-leverage observations and outliers using Huber weights and biweights.

[16] A detailed discussion of this calculation, based on an optimal control model of shifting cultivation, appears in a separate online appendix. This appendix is available at JEEM's online archive of supplemental material, which can be accessed at ⟨http://aere.org/journals/⟩.

[17] As discussed in López [8], the interest rate is a key parameter. Higher interest rates justify less fallow since the future value of the fallow biomass stock is discounted more heavily. In the absence of data on interest rates facing sampled farmers, I consider interest rates of 6%, 10%, and 20% to reflect the range in subsidized credit programs and market interest rates available to farmers in the region.

Table 5
Land allocation efficiency of sampled farms (1% significance test).

	Model (1) (%)	Model (2) (%)	Model (3) (%)	Model (4) (%)
6% interest rate				
Optimal fallow	26	52	89	77
Over-fallow	73	47	9	19
Under-fallow	< 1	< 1	2	4
10% interest rate				
Optimal fallow	25	42	82	71
Over-fallow	75	58	17	26
Under-fallow	< 1	< 1	1	3
20% interest rate				
Optimal fallow	20	33	71	63
Over-fallow	79	67	28	34
Under-fallow	< 1	0	1	3

a statistically significant amount by reallocating land between fallow and cultivation. The appearance of over-fallowing does increase (and under-fallowing decreases) if farmers face a higher interest rate, as they would have more reason to draw down on the stock of fallow to expand cultivation in the near term.

These results contrast those of López [7,8] and Goldstein and Udry [9], who found that farmers in Ghana and Cote d'Ivoire holding fallow in common property cleared excessive amounts of fallow for cultivation relative to the social optimum. This could suggest that private property ownership is one factor that improves efficiency of land management, though this inference is by no means definitive, considering the multitude of agroecological and socioeconomic differences between the study regions.

Positive externalities provide a social, but not individual, rationale for the maintenance of large fallow areas. The analysis presented here is not sufficient to assess the causes of over-fallowing—in particular, whether observed land management patterns are the result of a deliberate strategy to maximize community profits. One hypothesis is that farmers internalize local land management externalities through cooperative institutions or social norms, a phenomenon sometimes observed in natural resource management among traditional communities [40]. A deliberate cooperative land management strategy is not the only explanation for the prevailing management pattern, though. An alternative hypothesis is that market failures or barriers such as poor road access limit agricultural expansion below individual profit-maximizing levels, leading farmers to inadvertently fallow more than would benefit them individually. A related study suggests that the latter explanation accounts for over-fallowing in the Bragantina, since fallowing is associated with limited access to credit and transportation [41].

10. Conclusions

This study adds to the growing body of literature quantifying the value of forest resources for human livelihoods, specifically agriculture. Such knowledge is essential for policy makers involved in land-use planning and economic development in forested areas where poverty remains widespread. Fallow makes an important contribution to farm income in semi-commercial, smallholder agriculture in the Eastern Amazon by improving land quality and providing harvestable products. The econometric analysis indicates that fallow provides valuable ecological services to downstream farmers as well. These results are likely applicable to other areas of the Amazon, given that agroecological conditions in Bragantina are common throughout the region.

The results also suggest that Bragantina farmers generally allocate land between cultivation and fallow efficiently, even considering beneficial spillovers. This finding does not necessarily imply that farmers intentionally internalize the value of these services, but it could suggest that private land tenure plays a role promoting sustainable land management, given the contrast with other studies of shifting cultivation in common property tenure regimes that find overexploitation of fallow biomass.

Economic and social conditions that foster optimal levels of forest fallow may not prevail in much of the tropics, particularly given the widespread dearth of formal property rights. In addition, if market barriers currently contribute to limiting agricultural expansion, then forest cover loss is likely to accelerate in the future. However, policies to promote forest carbon sequestration, such as payments for REDD, could provide a countervailing force against forest cover loss in agroecosystems. They could also benefit communities by improving agricultural productivity if they are designed to incentivize locally beneficial spatial patterns of fallow management. Thus, knowledge of the local benefits of forest fallow may bolster efforts aimed at conserving tropical forests to mitigate greenhouse gas emissions and biodiversity loss.

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Appendix

See Table 6.

Table 6
First-stage equations for on-farm fallow variables.

	On-farm fallow	Upstream fallow (survey data)	Upstream canopy cover (GIS data)
Log farm size	0.210*	0.004	0.083*
	[0.118]	[0.045]	[0.045]
Owner	0.490**	−0.08	0.014
	[0.215]	[0.079]	[0.080]
Male household head	0.770***	−0.022	0.046**
	[0.053]	[0.021]	[0.021]
Log upstream farm size		0.597***	0.076***
		[0.034]	[0.025]
Upstream owner		0.123	0.116
		[0.103]	[0.075]
Log cultivated area	−0.094	−0.02	−0.031
	[0.073]	[0.028]	[0.028]
Log family labor	−0.046	0.056**	0.042
	[0.071]	[0.027]	[0.027]
Log hired labor	−0.004	−0.041**	−0.029
	[0.049]	[0.018]	[0.018]
Log chemical fertilizer	0.002	−0.023	−0.032*
	[0.048]	[0.018]	[0.018]
Use pesticides (binary)	0.229*	0.076	−0.139***
	[0.133]	[0.051]	[0.050]
Perennial producer (binary)	−0.032	−0.130***	0
	[0.129]	[0.048]	[0.049]
Use extension services (binary)	−0.06	−0.018	−0.078
	[0.131]	[0.049]	[0.050]
Charcoal-enriched soil (binary)	−0.065	−0.074	0.05
	[0.169]	[0.060]	[0.064]
Black clay soil (binary)	−0.326*	−0.075	0.097
	[0.177]	[0.066]	[0.068]
Slope	0.026	0.018**	0.038***
	[0.020]	[0.007]	[0.008]
No on-farm fallow (binary)	−1.639***	0.039	0.04
	[0.173]	[0.067]	[0.066]
No upstream fallow area (binary)		−1.334***	
		[0.154]	
No family labor (binary)	−0.204	0.303	0.011
	[0.526]	[0.189]	[0.198]
No hired labor (binary)	−0.005	−0.194**	−0.223***
	[0.210]	[0.078]	[0.079]
No fertilizer (binary)	0.071	0.068	−0.012
	[0.235]	[0.090]	[0.092]
Constant	−0.27	1.082***	4.565***
	[0.423]	[0.184]	[0.180]
Observations	268	234	258
R^2	0.72	0.86	0.42
Shea's partial R^2	0.46	0.62	0.06

Standard errors in brackets.
* Significant at 10%.
** Significant at 5%.
*** Significant at 1%.

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