ABSTRACT

Title of Dissertation: THE ECONOMICS OF FALLOW: EVIDENCE FROM THE EASTERN AMAZON

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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. In some tropical forests, such as the Eastern Brazilian Amazon, farmers practice a shifting cultivation system that maintains large amounts of land under forest fallow. I examine whether local benefits of fallowing such as soil restoration, erosion mitigation and hydrological regulation are of sufficient value to farmers to stem the expansion of permanent cropland at the expense of forest.

I quantify the value of ecosystem services provided by fallow to agriculture and test whether local forest externalities are economically significant, using farm survey and GIS data from the Eastern Amazon. I estimate a production function to determine the contribution of on-farm and upstream fallow to income, using an instrumental variables approach to address endogeneity. I find that on-farm and upstream fallow are both associated with higher farm income. This result both confirms the agronomic evidence that fallow boosts yields and suggests that fallow provides positive hydrological externalities to downstream farms.

I also examine whether farmers respond strategically to their neighbors' land use, taking advantage of ecosystem services provided by upstream farms. I use a spatial

econometric model to estimate the effect of upstream farms' fallow on downstream land allocation. I find no evidence that farmers alter their fallowing based on land use upstream.

I then investigate whether market failures encourage fallowing. If farmers cannot purchase inputs used in cultivation due to liquidity constraints, they may keep more land under fallow than optimal. I use the estimated production function parameters to determine whether each farm's allocation of land between cropping and fallow is efficient from an individual perspective. I then estimate the effect liquidity indicators on land use efficiency. I find that over-fallowing is negatively associated with commercial credit use and off-farm income, suggesting that liquidity constraints do hinder agricultural intensification. Because I find evidence to support the existence of positive externalities to fallow, the loosening of liquidity constraints that encourage fallowing has ambiguous implications for community-level welfare.

THE ECONOMICS OF FALLOW: EVIDENCE FROM THE EASTERN AMAZON

by

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1 Introduction

1.1 Tropical deforestation and shifting cultivation: a global issue

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. In some tropical forested areas, such as the Zona Bragantina in the Eastern Brazilian Amazon, farmers practice a shifting cultivation system that maintains large amounts of land under forest fallow. This study explores farmers' incentives for maintaining forest fallow, which provides many of the same environmental services as mature forests. I examine whether local benefits of fallowing such as soil restoration, erosion mitigation, and hydrological regulation are of sufficient value to farmers to stem the expansion of permanent cropland at the expense of secondary forest.

Shifting cultivation—the rotation of cropping and restorative fallow periods—has been practiced by farmers for thousands of years and is still common today as a form of traditional agriculture in tropical countries. The process involves clearing forested land for one or two seasons of cultivation, followed by long fallow periods in which forests are allowed to regenerate. An estimated 300 million people worldwide rely on this extensive form of farming for their livelihoods[1]. Shifting cultivation is likely to remain a predominant practice in tropical countries as expansion of settlement into forest areas continues and opportunities for small-scale farmers remain limited.

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[1] Current estimates of the number of shifting cultivators are hard to come by. The 300-million figure is given by Sanchez (1996) and Brady (1996).

Secondary forest fallow provides on-site benefits to farmers, such as soil restoration, erosion prevention, and weed and pest curtailment. It also provides off-site services, supplying some of the same local and global public goods as mature forests. Understanding the magnitude of secondary forests' contribution to agricultural productivity will be increasingly important as population and economic pressures spur farmers to shorten fallow periods, adopt new technologies, and intensify cultivation.

However, economic studies accurately estimating the value of forest hydrologic services are sparse, and results from hydrologic studies are themselves ambiguous as to the effects of reforestation on water yields (Bruijnzeel 2004). Valuing the net benefits of forest cover to local populations may also help justify forest conservation efforts with global importance (Chomitz and Kumari 1998). The Millennium Ecosystem Assessment (2005) has identified lack of information about the value of non-market ecosystem services as a major knowledge gap hampering informed decision-making on ecosystem management. The Assessment also calls for improved information on the economic consequences of ecosystem changes and the links between human welfare and ecosystem services, particularly regulating services such as erosion, hydrological, and climate regulation.

I take up this challenge by quantifying the returns to fallowing in agricultural production. I estimate separately the value of on-farm and off-site services supplied by forest fallow to determine whether fallow provides economically significant local externalities that may justify forest conservation from a local or regional perspective. I also investigate whether farmers allocate land between cultivation and fallow strategically, responding to land use on other farms. Finally, I examine potential barriers to efficient fallow management, such as liquidity constraints that may promote fallowing at the expense of intensified cultivation.

1.2 Valuation of fallow biomass resources: a review

The study builds upon existing research that has examined the role of fallow and forest biomass in agricultural productivity. While few empirical studies provide estimates of the value of fallow biomass and forest cover in agricultural production, those that do find that it provides economically important services. López (1993, 1997, 1998) finds village-level fallow biomass to contribute significantly to agricultural profitability in Ghana and Cote d'Ivoire, with a factor share varying between 0.15 and 0.2. This strong effect captures both on-farm soil quality and external hydrological benefits since farm- and community-level biomass are likely to be highly correlated. Mendoza (2004) uses the same data set as the present study to estimate the contribution of fallow length to plot-level cassava profits, finding a positive but not statistically significant effect. However, the author does not control for the endogeneity of fallow management. Another study estimates the on-farm value of agroforestry practices in improving soil quality in the Philippines (Pattanayak and Mercer 1998). When balanced against the opportunity cost of the land and labor used to maintain hedgerows, the net benefits are positive but small.

Some off-site ecosystem services associated with forest cover have been quantified recently as well. A study in Ruteng National Park, Indonesia, uses hydrological modeling to link nearby forest cover to baseflow and to measure the returns in agricultural production (Pattanayak and Kramer 2001, Pattanayk and Butry 2005). Increases in baseflow significantly raise farm profits, but the effect of afforestation on baseflow is projected to vary considerably over space. Small forest patches harboring bees provide crop pollination services to a coffee plantation in Costa Rica worth $60,000 per year (Ricketts et al. 2004).

Other research emphasizes the costs to farmers from livelihoods based on slash-and-burn. Smoke can cause respiratory illness, and accidental fires lead to property damage, with one study estimating costs on the order of 0.2% of regional GDP (Mendonca et al. 2004, Varma 2003). These problems have prompted interest in "alternatives to slash-and-burn"—land-use options to achieve the dual goals of poverty reduction and forest conservation (Tomich et al. 1998). Suggested technologies include enriched fallows, a technique involving seeding fallowed plots with leguminous and fast-growing trees to speed soil recovery, and "fire-free" land preparation using chop-and-mulch machinery (Kato et al. 1999). While my study does not examine the negative externalities arising from the use of fire in shifting cultivation, a full accounting of the net benefits of fallow must incorporate these costs.

1.3 Case study: the Eastern Amazon's Zona Bragantina

The Zona Bragantina offers a compelling case study as a region with over one hundred years of agricultural settlement where shifting cultivation persists as the principal means of livelihood. The course of economic development and land use in Bragantina may provide insights for frontier regions now being rapidly settled throughout the Amazon. Despite integration into regional markets through railways and roads, perennial cash-crop production and processing, and government programs to encourage agricultural intensification, shifting cultivation dominates other land-use practices in the region.

While virtually all virgin forest in Bragantina has been cleared in previous decades, roughly 75% of the land area remains under secondary forest (Kato et al. 1999). Conversion of land from virgin forest to shifting cultivation results in net losses of above-ground carbon stocks, but below-ground carbon storage remains stable due to the secondary forests' extensive root systems (Sommer 2000). Transition to permanent cropping would entail significant losses of both above- and below-ground carbon. Therefore, current land use in the Zona Bragantina provides a carbon sink that helps mitigate global climate change. However, a linear programming model of the region predicts that farmers will significantly decrease average fallow lengths over the next 25 years, with corresponding net increases in carbon dioxide emissions (Borner 2005).

Bragantina is among the longest colonized and most densely populated regions of the Amazon, but severe challenges remain for poverty alleviation and development. Incomes remain low by Brazilian standards. Per capita income in Bragantina is less than 75% of the Pará average. Meanwhile, Pará ranks 17th out of 27 states in terms of human development, and 58% of households in rural areas make insufficient income to meet basic food needs (Verner 2004). Population growth in Bragantina fell during the 1990s to 1.8%, below the Brazilian average of 2%.

1.4 Contribution of this study

I develop a conceptual model of shifting cultivation in the context of the optimal control literature on soil fertility and fallow management. This model distinguishes between the on-site benefits of fallowing and the positive externalities of secondary forests. I use this model to explore the implications of decentralized versus collective management and liquidity constraints for land use efficiency. I show that liquidity constraints can encourage over-allocation of land to fallowing by limiting purchased inputs used in cultivation. The implications of such constraints for community welfare depend on the existence of positive externalities to fallow and whether fallow is managed collectively to account for such externalities.

The empirical analysis uses cross-sectional farm-level survey data from the Zona Bragantina to assess the value of forest fallow services to farmers and test whether externalities generated by secondary forests are economically significant in agriculture. Well-established private land tenure in the study region allows me to disentangle the on-farm and externality effects. I first estimate a crop production function, measuring the contributions of on-farm and off-farm forest fallow as factors of production. I then estimate a forest product equation to determine the contribution of forest fallow to harvested products. I address endogeneity issues using an instrumental variables approach, as well as modeling spatially-correlated errors to account for variation in unobservable factors over space.

I use geographic information on the location of farms to obtain data on cross-sectional external forest fallow and other agroecological factors at the farm level. The geographic data improves the specification of the external forest fallow variable, though I do not explicitly model the underlying mechanism of the ecosystem services provided by on- and off-farm forest fallow. While fallowing entails dynamic processes that cannot be fully captured with cross-sectional data, I use the area under fallow at the time of the survey to infer fallow biomass density, considering the long settlement history and relatively constant farming practices and demographics in the study region over the past several decades.

I also investigate using a spatial econometric model whether farms allocate land between cultivation and fallow strategically, based on their neighbors' land use, to take advantage of any positive externalities arising from forest fallow. Farmers who receive a productivity boost from their neighbor's forest fallow may shift their own allocation of land towards cultivation to exploit these services. Identifying this effect is complicated by the potential underlying spatial correlation of unobserved factors that may influence farmers' and their neighbors' land use decisions in similar ways. I address this concern by allowing for spatial correlation in the error of the fallow equation to capture the effects of any unobserved variables varying over space that may spur neighboring farms to make similar land allocation decisions.

I then use the estimated value of forest fallow services to examine whether farmers in the Zona Bragantina may be allocating land between cultivation and fallow inefficiently due to market failures or other constraints. Ecological studies documenting the restorative effects of fallowing on soil quality do not consider the tradeoffs inherent in allocating land to fallow rather than cultivation. While long fallow periods can be a cost-effective way to restore soil quality and obtain harvestable products for consumption or sale, fallowing becomes more costly when the opportunity costs of land and labor are considered. Land must remain out of cultivation for years at a time to ensure sustainability of the system, and clearing land of forest fallow requires large amounts of labor time. The total returns to fallowing thus depend on the relative contributions of fallow and cultivated land to farm income, as well as the cost of labor used in land clearing.

If forest fallow does provide positive local externalities, these ecological services provide a social, though not individual, rationale for the maintenance of larger fallow areas than is privately optimal. Credit and off-farm employment constraints and other market failures offer alternative, though not mutually exclusive, explanations for the persistence of long fallow periods, as I discus in the theoretical model. I consider various socioeconomic and agroecological factors as possible determinants of fallow management efficiency, using the results of previous studies on tropical deforestation to inform the analysis.

Implications of market failures for fallow management efficiency depend on the magnitude of local forest externalities. Market imperfections that encourage fallowing may be welfare-improving for the community if forest fallow provides economically significant local externalities. However, constraints in the absence of positive local externalities may hinder farmers' expansion of profitable agricultural activities, suggesting that the rate of deforestation is likely to increase as farmers' access to markets improves.

2 Ecology and socioeconomics of shifting cultivation in Eastern Amazonia

Where land is abundant and other inputs are scarce, long fallow periods can be a cost-effective way to regenerate soil fertility, control pests and weeds, and otherwise restore land for future agricultural uses. Farmers typically clear forested land by slash-and-burn: vegetation is cut to the ground, the organic matter is dried and then burned, and the ash is used to fertilize the soil.

2.1 Agricultural profile of the Zona Bragantina

In the Zona Bragantina of Pará state in the Eastern Brazilian Amazon, traditional farmers (*caboclos*) have made shifting cultivation a mainstay of the economy for over a century of settlement. The Brazilian government initially promoted colonization in the mid-19th century to supply the food needs of the state capital, Belém. Despite government initiatives to promote intensive cash crop production, shifting cultivation remains the predominant livelihood. Virtually all of the virgin forest in the region has been cleared for several decades, but secondary vegetation covers approximately 75% of the total land area (Kato et al. 1999)[2]. Figure 1 presents a map of the region.

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[2] Satellite data (e.g., Moran 1994) and farm surveys (e.g., Smith et al. 1999) reveal that secondary forests make up a considerable portion of once-deforested land throughout the Amazon—around 30%, according to some estimates (Houghton et al. 2000).

Figure 1 Municipios in the Zona Bragantina

Source: http://pt-uf.pt-dlr.de/Shift/english/map/env101.htm, Accessed Nov. 28, 2005

Interspersing short periods of annual cropping with long fallows on landholdings of around 25 hectares, farmers use fallow vegetation (termed *capoeira*) as a natural capital input into crop production. While family labor and manual land clearing and cultivation predominate, hired labor and mechanized equipment may also be used for labor-intensive tasks like land preparation, weeding, and harvesting. A typical one to two year cropping sequence includes maize, upland rice, and cowpea, with cassava grown as the final crop while fallow vegetation reestablishes (Holscher et al. 1997a). These annual crops are used for home consumption and sale to regional markets.

Since the mid twentieth century, smallholders have also branched into perennials like black pepper, passion fruit, oranges, and coconut, as well as cattle production. Perennial cultivation requires use of chemical fertilizers and pesticides, which farmers also occasionally apply to annuals (Hedden-Dunkhorst 2003). The initial costs of establishing a black pepper plantation, estimated at US$3650 by one study, remain prohibitive for many farmers, particularly since it yields no crop for the first two years after planting before the ten year production cycle begins (Toniolo and Uhl 1995). Government programs to promote perennial cash crops, such as financing agro-processing facilities in the region, spurred increased adoption in the 1970s and 1980s. Since then, widespread pest infestations and price fluctuations have dampened enthusiasm for passion fruit and black pepper production (Mendoza 2004).

Binswanger (1991) has documented myriad policies, from agricultural credit to tax incentives, that fostered conversion of forests to other land uses and concentration of farms into large landholdings during the twentieth century. More recent policies have sought to reverse the trend by funding subsidized credit for small farmers and restricting use of forested areas. Prorural provides old-age pensions, originally offering 50% of the legal minimum salary, which was raised to 100% in 1991. The same year saw the introduction of the FNO[3] credit program targeting smallholders with loans of $B5000 at 6% interest. While technically accessible to all small-scale farmers, loans were reserved for those with access to extension services and plans to invest in perennial production.

In the 2000s, the government established Proambiente, still in its pilot phase, to promote economic development and environmental conservation goals concurrently. The new initiative seeks to compensate farms for adopting purportedly sustainable agricultural practices by relaxing the terms of agricultural credit and subsidizing certain technologies (Nepstad et al. 2004). Encouraged practices include reforestation of degraded lands and chop-and-mulch instead of slash-and-burn land clearing. Chemical fertilizer use is prohibited for borrowers. A simulation model of Proambiente in the Zona

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[3] The Fundo Constitucional de Financiamento do Norte, established in 1988 by constitutional mandate, is financed by federal tax revenues.

Bragantina raises skepticism about the likelihood of achieving increased farmer incomes though this program (Borner 2005).

The Brazilian government has also enacted laws to prevent excessive forest clearing on privately owned farms. Riparian forests hold protected status, and the "Forest Code" requires farms to maintain 50% of their land under forest cover. While compliance with the former law is high in the Zona Bragantina, awareness of the latter policy is low, and the law is ambiguous regarding secondary forests (Borner 2005).

The region faces major challenges in improving agricultural productivity due to poor quality Oxisol, Spodosol, and Ultisol soils that are vulnerable to acidity and aluminum toxicity (Tucker et al. 1998, Holscher et al. 1997). Experiments varying fertilizer treatments in the Zona Bragantina identified phosphorus and nitrogen as major limiting factors in crop production and fallow biomass growth (Gehring et al. 1999).

Soil is relatively homogenous in the region, though rainfall does decrease along a gradient from west to east (Borner 2005). The climate is humid, receiving an average rainfall of 2400-2700 mm annually. Much of the Zona Bragantina lies on *terra firme*, land that does not lie directly in the floodplain. However, farmers in the sample do report excess rainfall and drought as two main sources of risk and have had to abandon land after flooding caused by heavy rainfall (Borner 2005).

Farmers are motivated to keep large areas of farmland under forest fallow by important on-site benefits. In the Zona Bragantina, forest products like wood, charcoal, and fruits make up around 7% of household income on average (Hedden-Dunkhorst et al. 2003). Settlers in the Peruvian Amazon allow secondary vegetation to reestablish largely for soil recuperation, though they are also spurred by timber harvesting and lack of resources for cultivation (Smith et al. 1999). Shifting cultivators near Altamira, Pará, leave land under fallow to restore soil fertility and control pests and weeds (Silva-Forsberg et al. 1997).

The exact role of fallow and biomass burning in crop production is still inadequately understood. For instance, field studies on maize in Pará found yields to be positively associated with fallow length but, surprisingly, to be lower on land cleared from mature than secondary forest (Silva-Forsberg et al. 1997). A review of several studies on fallow does not find a conclusive link between decreased fallow age and declining yields, though studies from the Eastern Amazon do exhibit such a relationship (Mertz 2002).

2.2 On-site effects of secondary forest

Recent agronomic research in the study area has shed light on a number of the on-site restorative functions of fallow vegetation (e.g., Nepstad et al. 2001, Holscher et al. 1997a, Sommer et al. 2000, Gehring et al. 1999). These on-site services can be characterized as stock effects that benefit the farmer when land is cleared and cultivated. Forest cover improves soil fertility and porosity, prevents surface erosion, and controls weeds and pests, creating a stock of high quality soil that contributes to agricultural productivity.

Trees improve soil structure through their deep root systems, which increase soil permeability to water, retrieve minerals from deeper levels of soil, and bring them to the surface in the form of biomass. Redistribution of nutrients from deep in the soil to the surface through leaf litter can raise the levels of phosphorus, carbon, potassium, nitrogen, calcium, and magnesium available to other plants (Altieri 1995). Secondary forests in the

Eastern Amazon have root systems several meters deep that are just as extensive as those of mature forests (Nepstad et al. 2001, Sommer et al. 2000). Their root systems also have higher rates of mycorrhizal infection than mature forests. These nitrogen-fixing bacteria allow secondary vegetation roots improved access to deep soil nutrient stocks (Nepstad et al. 2001). Secondary forest roots may also obtain deep soil nutrients in solution during water uptake. The roots tend to remain intact after manual land clearing, fostering rapid vegetative regeneration during initial fallow years (Holscher 1997a).

When fallow biomass is burned in preparation for planting, the resulting ash is rich in minerals that fertilize the soil. The alkaline ash and increased mineral availability also raise soil pH, which is particularly beneficial in regions of acidic soil (Altieri 1995). An experiment in the Zona Bragantina converting seven-year fallow to cultivation with slash and burn found increases in soil pH, cation exchange capacity, potassium, calcium, and magnesium in the surface soil layers due to plant ash (Holscher et al. 1997a). Burning can also kill weeds and weed seeds, insect pests, bacteria, and fungi.

Drawbacks of biomass burning include nutrient loss through volatilization and decreased uptake of nutrients, leaving the soil vulnerable to leaching of the valuable nutrients (Gliessman 1998). Other temporary effects of burning on soil include reduced soil moisture retention and permeability, decreased organic matter, and reduced populations of soil microorganisms, but these effects can be quickly moderated by the reintroduction of vegetation. Poorly managed slash-and-burn systems are vulnerable to nutrient loss, soil erosion, and invasion of weedy or undesirable plant species (Gliessman 1998). In well-managed slash-and-burn systems, the soil retains high levels of carbon and nitrogen, tree roots, and myccorhizae.

In high rainfall areas like the Amazon, surface erosion is minimized by rapid vegetation regrowth on abandoned plots (Sanchez et al. 1982). In the tropics, erosion rates on land under fallow vegetation are comparable to those in natural forests but rises considerably during cultivation. However, forest cover has less impact on gully erosion and mass wasting (Bruijnzeel 2004).

While any type of vegetative ground cover hinders surface erosion, tree canopy cover is critical in weed suppression (de Rouw 1995). In the first phase of weed control after fallowing, rapidly reestablishing secondary vegetation crowds out weed species. In the second phase, woody species create a canopy that shades the soil, decimating the weed seed bank (Staver 1991). Shorter fallow periods exacerbate weed infestation when the land is brought into cultivation, creating a vicious cycle of diminished agricultural productivity and delayed secondary forest succession in subsequent fallow periods. Farmers in the Zona Bragantina report that weeding demand more than doubles when slash-and-burn land preparation is not used (Borner 2005).

Longer fallow periods are associated with higher agricultural productivity in eastern Amazon sites. In a study near Altamira, Pará, maize yields under traditional *caboclo* cropping increased significantly with fallow age (Silva-Forsberg et al. 1997). An experimental study in the Zona Bragantina documented reduced rice yields on plots fallowed for four instead of ten years, though fertilizer application narrowed the yield gap considerably (Kato et al. 1999).

2.3 Off-site services of secondary forest

Besides providing a stock of soil nutrients and weed control that benefits the farmer when the plot is brought into cultivation, standing forest fallow provides a flow of environmental services, some of which may enhance agricultural productivity locally or regionally. Forest cover has the potential to affect nearby farms' productivity through the hydrological cycle, crop pollination, and tree seed availability. Few studies indicate whether farmers are likely to reap economically significant benefits from these effects.

Secondary forests in the Amazon perform largely the same hydrological functions as mature forests, mitigating the effects of deforestation. Their deep and extensive root systems extract soil water from lower layers (Nepstad et al. 2001). Meteorological data show little difference in evapotranspiration rates between young secondary vegetation and mature forest in the Eastern Amazon (Holscher et al. 1997b). Simulation models of precipitation in the Amazon suggest that minimal changes in rainfall from deforestation are expected due to the prevalence of secondary vegetation in deforested areas.

Tree cover (whether mature forest or secondary vegetation) plays an important role in the hydrological cycle, both reducing erosion rates on-site, as discussed above, and affecting water yield and distribution over space and time. Forest cover moderates peak flows and surface runoff due to increased soil infiltration capacity and evapotranspiration of soil water (Hamilton and King 1983, Bruijnzeel 2004), which may benefit agricultural activities by lessening floods and waterlogging. The effect of vegetation cover on storm flow becomes less important with higher rainfall intensity, as soil infiltration capacity is quickly overwhelmed in extreme rainfall events.

Improved infiltration may also lead to increased dry season baseflow in some cases, although this effect is not well documented by the scientific literature (Calder 2002, Bruijnzeel 2004). A study examining the value of off-farm forest cover in Ruteng National Park, Indonesia, does find positive returns to drought mitigation services provided by local forest cover to small-scale agricultural production (Pattanayak and Kramer 2001, Pattanayak and Butry 2005). However, the agroecology of the Indonesian case, with its steep slopes and packed, clay soils, contrasts with the conditions in the Eastern Amazon, which has relatively flat slopes and sandy soils, making it conducive to soil water infiltration even without extensive tree cover.

Changes in water yield due to deforestation have been documented on a small scale, but the effects are less clear on a larger catchment level (Bruijnzeel 2004). My research focuses on localized farm-level changes within the Zona Bragantina, since a cross-regional watershed-scale study is not feasible with the data at hand. To my knowledge, no studies have examined whether farmers realize agricultural benefits from forest hydrological services in the Amazon.

Natural habitat such as forest fallow may also provide crop pollination services to nearby farms by harboring bees and other insects. Cereal and root crops grown in the Zona Bragantina, such as maize and cassava, do not rely on insect pollinators. However, many widely-grown high-value horticultural crops do, including passion fruit, black pepper, and watermelon. Studies estimating the spatial scale of crop pollination find bees pollinate crops within 1-2.5 km of natural habitat, closely tracking their typical foraging ranges (Ricketts et al. 2004, Kremen et al. 2004). Pollination services from nearby forest patches of 46-111 hectares increased coffee yields by 20% in Costa Rica (Ricketts et al. 2004).

Nearby forest stands are also important for succession of fallowed plots from scrub and weedy vegetation to forest. Woody plants reestablish on fallowed plots not only from roots remaining in the soil after cultivation, but also from seeds disbursed by neighboring forests (Nepstad et al. 2001). Nearby forest stands can ultimately improve regional agricultural productivity by speeding up restorative secondary vegetation growth on fallowed plots. A field study in Pará attributes low forest regrowth rates in some Zona Bragantina sites to poor soils and a dearth of mature forest stands (Tucker et al. 1998).

While hydrological, pollination, and tree seed availability can be characterized as positive externalities, ecological services provided by forest fallow may be so localized that they occur largely within-farm and not off-site, considering the relatively large farm sizes that prevail in the region (40 hectares on average). In addition, these ecological services may act as substitutes if on- and off-farm fallow provide similar erosion control, soil water regulation, and crop pollination functions locally.

Based on the above discussion, the scientific literature supports the idea that localized externalities provided by forest cover may enhance agricultural productivity by reducing peak water flows and surface runoff, providing habitat for bees and other insect pollinators, and serving as a source of tree seeds. Larger scale, regional level hydrological externalities are possible but are not well explained by the current state of research. For the purposes of this study, I do not focus on other regional or global externalities provided by forest fallows or shifting cultivation, such as carbon storage, biodiversity habitat, or air pollution from biomass burning.

3 A conceptual model of shifting cultivation

3.1 Optimal control of fallow biomass: a review

Determining the optimal maintenance of fallow biomass presents a standard renewable resource problem in which the current net benefits of farming must be traded off against discounted future productivity. The resource can be considered a stock of land quality that contributes to agricultural productivity. Studies that consider fallow biomass or soil as a resource stock that evolves over time based on agricultural use and natural regeneration provide the starting point for this analysis.

Beginning with McConnell's (1983) analysis of soil management, optimal control models have been used to examine the conditions under which farmers augment or deplete the stock of land quality over time. Models of shifting cultivation (e.g., Larson and Bromely 1990, Barrett 1991, Krautkraemer 1994) specify land quality regeneration as a function of fallow length or area. Assuming no externalities or market failures, depletion of the resource stock does not necessarily imply inefficient management. Private and socially optimal management are not expected to diverge unless the farmer has a different rate of discount than society (McConnell 1983). Farmers facing a nonconvex net benefit function may prefer cyclical cultivation and fallows to continuous farming at a steady state of soil quality (Krautkraemer 1994). Population pressure is one factor that may spur shortened fallows as a form of agricultural intensification. These studies do not incorporate typical developing country market failures, such as limited access to employment and credit. Romano (2003) addresses this gap, acknowledging the ambiguous effects of these market constraints on soil conservation[4].

Managing land quality through shifting cultivation entails allocating land between fallow and cultivation to balance current and future productivity. Hartwick, Long and Tian (2001) examine permanent land conversion from forest to cropping, where the equilibrium land allocation balances the marginal profit of sustainable forestry with that of one-off timber harvesting followed by agriculture. When the initial stock of forested land exceeds the steady state level, a period of rapid land clearing ensues until the optimum is reached. Ehui, Hertel and Preckel (1990) capture the land allocation tradeoff by modeling agricultural production as a function of the deforestation rate and the cumulative amount of deforested land (the former affecting yields positively, the latter negatively). While the authors assume cumulative deforestation to dampen yields by bringing more marginal land under cultivation, this specification can also represent a loss of positive externalities provided by the forest stock.

López (1993, 1997, 1998) also confronts the land allocation problem by explicitly linking cultivated land area and fallow biomass density. The fallow biomass stock is considered a village-level common property resource that contributes to agricultural productivity by providing environmental services. In the absence of community-level management, individual households undervalue the shadow cost of lost biomass and allocate too much land to cultivation, decreasing income for the village as a whole.

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[4] Romano's empirical results show that El Salvadoran farmers facing market constraints increase soil conservation with improved access to liquidity but decrease conservation with more off-farm employment.

3.2 A model of shifting cultivation

Here I extend López's model to examine the inefficiencies that may arise in fallow management even under private land ownership. When fallows are not a common property resource, externalities associated with forest clearing still create the scope for inefficient management. Farm-level fallow biomass (θ(t)) equals the land area left fallow ($\overline{X}_i - x_i(t)$)multiplied by the average biomass density (η(t)).

$$\theta_i(t) = \eta_i(t)\left(\overline{X}_i - x_i(t)\right)$$

As in the biomass density growth function proposed by López (1993), a greater fraction of land under cultivation entails shorter fallow periods on average and hence less biomass accumulation because land as regularly rotated between cropping and fallow. Average biomass density on fallow land is thus assumed to decline with the biomass extracted during land clearing and increase at a constant rate (b) according to the following equation.

$$\dot{\eta}_i(t) = b - \frac{\eta_i(t)x_i(t)}{\overline{X}_i}$$

By focusing on the allocation of land, this specification suppresses the length of cultivation and fallow cycles as a choice variable. Instead, it sharpens the focus on the overall level of fallow biomass at any given time.

While López treats the village-level stock of fallow biomass as one factor of production, I allow fallow biomass to boost productivity through two separate effects—average on-farm biomass and local or village-level biomass. These two effects capture the private soil-enhancing benefits and positive hydrological or other externalities of forest fallows. While the farmer is likely to bring the oldest fallow into production, López (1993) establishes the proportionality between average and marginal biomass density, assuming a constant growth rate. I also assume private land ownership so that fallow biomass is not a common property resource, but rather a private resource supplying externalities[5].

The production function for farm i is given by

$$Af^{i}\left(x_{i}(t), l_{ci}(t), z_{i}(t), \theta_{i}(t), \overset{N_i}{\underset{j}{\Sigma}} \theta_{j}(t) \right)$$

where x(t) is cultivated area and $l_c(t)$ is cultivation labor. I also introduce a choice variable to represent purchased inputs, such as chemical fertilizer (z(t)). The production function is increasing and concave in all inputs. A is a factor-neutral productivity shifter. I assume all factors to be gross complements. N_i represents the number of farms that provide ecological services to farm i. Since hydrological regulation is one externality of particular interest, N may include only those farms upstream of farm i but not those downstream or outside of the sub-watershed. N_j gives the number of farms that farm i affects.

On-farm fallow biomass has an additional productive use as a source of forest products that can be harvested for consumption or sale. Forest product harvests are a function of harvesting labor and fallow biomass, as well as off-farm fallow if hydrological, pollination, or other ecological services also improve forest product yields, as below:

$$h^{i}\left(l_{hi}(t), \theta_{i}(t), \overset{N_i}{\underset{j}{\Sigma}} \theta_{j}(t) \right)$$

I assume that the fallow product harvesting function is increasing and concave in labor and on- and off-farm biomass, and that these factors are all gross complements. Unlike crop production, I assume that no purchased inputs are used in forest product

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[5] Private land ownership is common in settled areas of the Brazilian Amazon like the Zona Bragantina.

collection and that factor-neutral productivity changes such as technology improvements do not boost yields. These assumptions are borne out in the current conditions of the Zona Bragantina but could easily be relaxed in an extension to this analysis.

Cultivated land area and biomass density also increase the cost of land clearing, as in Dvorak's (1992) model of shifting cultivation. To ensure concavity of the objective function, I assume the clearing cost function to be linear in land area and biomass density. Although land clearing is typically manual in the Zona Bragantina, I capture the cost with the constant parameter c since clearing labor is needed only briefly at the start of the season.

Each farm's profits encompass the revenue from crops and products harvested from the forest fallow, minus the costs of land clearing, labor, and purchased inputs. The price of fallow products is given by q, while p, v, and w represent output and input prices and the wage rate, respectively. The discount rate is given by r. Suppressing the time argument, the farm profit function is

$$\Pi_i = qh^i\left(l_{hi,}\theta_i, \sum_{j}^{N_i}\theta_j \right) + pAf^i\left(x_i, l_{ci}, z_i, \theta_i, \sum_{j}^{N_i}\theta_j \right) - cx_i\eta_i - w(l_{hi} + l_{ci}) - vz_i \tag{1}$$

If households have access to well-functioning markets, farm production is recursive and independent of household characteristics. However, even when access to markets is imperfect, a complication I introduce later in the discussion, household production behavior can be represented by profit maximization rather than utility maximization under the assumption of fixed leisure. Each farm household thus confronts the following problem.

$$\max_{x_i, l_{hi}, l_{ci}, z_i} \int_0^\infty \Pi e^{-rt} dt \quad \text{s.t.} \quad \dot{\eta}_i = b - \frac{\eta_i x_i}{\overline{X}_i}, \eta_i(0) = \eta_0, x_i \le \overline{X}_i$$

Now I turn to the conditions characterizing farmer choices under different institutional arrangements. I consider five cases: centralized (or collective) fallow management, collective fallow management with labor market imperfections, decentralized fallow management, decentralized fallow management under liquidity constraints that affect all farmers equally, and decentralized management under unequal liquidity constraints. I focus on liquidity constraints because access to purchased inputs has important implications for fallow maintenance. These different scenarios of efficient and inefficient management highlight the conditions under which farmers expand or deplete the stock of fallow biomass.

3.2.1 Case 1: Centralized or collective management of fallows

Under centralized or cooperative fallow management, the optimal input levels are determined by maximizing the sum of farm profits over the entire sub-watershed. The Hamiltonian and necessary conditions for this problem are

$$H = \sum_{i}^{N} \left\{ qh^{i}\left(l_{hi}, \theta_{i}, \overset{N_i}{\underset{j}{\Sigma}} \theta_{j} \right) + pAf^{i}\left(x_{i}, l_{ci}, z_{i}, \theta_{i}, \overset{N_i}{\underset{j}{\Sigma}} \theta_{j} \right) - cx_{i}\eta_{i} \right\}$$

$$- \sum_{i}^{N} \{ w(l_{hi} + l_{ci}) - vz_{i} \} + \mu_{i}\left(b - \frac{\eta_{i}x_{i}}{\overline{X}_{i}} \right)$$

$$H_{x_i} = -q\eta_i h_2^i - q\eta_i \overset{N_j}{\underset{j}{\Sigma}} h_3^j + pAf_1^i - pA\eta_i f_4^i - pA\eta_i \overset{N_j}{\underset{j}{\Sigma}} f_5^j - c\eta_i - \frac{\mu_i\eta_i}{\overline{X}_i} \leq 0, \tag{2}$$

$$x_i \geq 0, H_{x_i} x_i = 0$$

$$H_{l_{hi}} = qh_1^i - w \leq 0, l_{hi} \geq 0, H_{l_{hi}} l_{hi} = 0 \tag{3}$$

$$H_{l_{ci}} = pAf_2^i - w \leq 0, l_{ci} \geq 0, H_{l_{ci}} l_{ci} = 0 \tag{4}$$

$$H_{z_i} = pf_3^i - v \leq 0, z_i \geq 0, H_{z_i} z_i = 0 \tag{5}$$

$$H_{\eta_i} = q\left(\overline{X}_i - x_i\right)h_2^i + q\left(\overline{X}_i - x_i\right)\overset{N_j}{\underset{j}{\Sigma}} h_3^j + pA\left(\overline{X}_i - x_i\right)f_4^i + pA\left(\overline{X}_i - x_i\right)\overset{N_j}{\underset{j}{\Sigma}} f_5^j \tag{6}$$

$$-cx_i - \frac{\mu_i x_i}{\overline{X}_i} = r\mu_i - \dot{\mu}_i$$

$$b - \frac{\eta_i x_i}{\overline{X}_i} = \dot{\eta} \tag{7}$$

$$\lim_{t \to \infty} e^{-rt} \mu_i \geq 0, \lim_{t \to \infty} e^{-rt} \mu_i \eta_i = 0 \tag{8}$$

The first condition (equation (2)) states that the marginal benefit of land under cultivation should equal the marginal costs in terms of land clearing, foregone net revenue of forest products, foregone positive externalities to other farms, and the shadow value of the lost fallow biomass density. Labor is allocated to equate the marginal benefits of harvesting forest products and cropping with the wage rate, from equations (3) and (4). Purchased inputs are similarly chosen to equalize the marginal value of increased productivity and the price (equation (5)). The shadow value of the biomass density stock evolves with the discount rate minus the marginal contribution of biomass density to farm profits (equation (6)). If the initial biomass density stock exceeds the steady state level, then the shadow value will start out low and rise over time while the stock is depleted until the steady state is reached, since, as shown by Long (1979), the stock and costate variables tend to move in opposite directions.

In the long run equilibrium, at which η and μ reach steady state levels, biomass density and total biomass are inversely proportional to the share of land under cultivation such that $\eta_i = \frac{b\overline{X}_i}{x_i}$ and $\theta_i = b\overline{X}_i\left(\frac{\overline{X}_i}{x_i} - 1\right)$. I derive the steady state comparative statics to infer how price and other parameters affect the level of fallow maintained by farmers[6]. In addition, by assuming other farms are also in equilibrium and taking their fallow biomass

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[6] I rewrite the maximization problem using duality to facilitate the derivation of comparatives statics, replacing fallow harvesting and crop production functions with net revenue functions maximized with

as given, I determine the effect of external fallow on the ith farmer's land allocation and biomass. Appendix A presents derivations for the comparative statics.

Table 3.1 Comparative statics with centralized fallow management and complete markets

	dq	dr	dp	dA	db	d$\theta_{j\neq i}$	dw	dv
dx_i	-	+	?	?	?	?	?	?
dθ_i	+	-	?	?	?	?	?	?

Forest product prices have the anticipated effect, increasing fallow biomass and reducing cultivated land. A higher rate of interest encourages expansion of cultivated area at the expense of fallow. Marginal increases in total factor productivity and biomass growth rate both have ambiguous implications for the stock of biomass. The biomass growth rate affects the biomass stock ambiguously because the positive direct effect may be outweighed by the indirect effect of a possible decrease in fallowed area. This latter point is of particular interest for the Brazilian Amazon, where "enriched fallow"—seeding fallowed land with leguminous and fast-growing trees to speed soil recovery—is a new technology being disseminated to boost farm productivity.

Cultivated land and fallow also respond to changes in the fallow biomass maintained on neighboring farms. This response depends on the relative strengths of the externalities contributed to forest product harvesting and crop production. If forest product externalities are sufficiently greater than crop production externalities, farm i increases the land under fallow, taking advantage of the additional productivity. If crop production externalities dominate, the opposite occurs.

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respect to fertilizer and labor. The resulting maximization problem is

$$\sum_i^N \left\{ V^i\left(\theta_i, \sum_j^{N_i} \theta_j ; q, w\right) + F^i\left(x_i, \theta_i, \sum_j^{N_i} \theta_j ; p, A, w, v\right) - c x_i \eta_i \right\} + \mu_i \left(b - \frac{\eta_i x_i}{\overline{X}_i}\right).$$

Increases in the wage rate also affect land allocation ambiguously. If the marginal productivity of land used in forest product harvesting exceeds that used in cultivation, a wage increase draws labor out of farm production, dampening the pressure to expand cultivation and exploit biomass. The reverse may be true if labor has a higher marginal productivity in crop production. These results depend on the existence of perfect labor markets, an assumption I relax in the next section.

Increases in the crop output price, factor productivity parameter, and input price also have unclear effects on fallow management without further knowledge about the crop production functional form. I assume a Cobb-Douglas technology for both crops and forest products in the remainder of the analysis to draw further intuition about the potential effects of various parameters on fallow management.

Under the Cobb-Douglas assumption, higher crop output prices and increased factor productivity cause an expansion in cultivated area and a contraction of the biomass stock. Similarly, increases in purchased input prices cause a contraction in the cultivated area and an expansion of fallow because the marginal cost of forest product harvesting remains the same, while that of cultivation rises. Note that even without the Cobb-Douglas assumption, this result still holds if purchased inputs complement cultivated land more strongly than fallow.

Input prices can also incorporate effectiveness, representing the per-unit cost of productivity enhancement. A drop in effectiveness is equivalent to a price increase, resulting in lower cultivated land and higher fallow biomass. Variations in the effectiveness of inputs such as fertilizer over space may thus lead to different levels of biomass exploitation.

Table 3.2 Comparative statics with centralized fallow management and complete markets (Cobb-Douglas production)

	dp	dA	dv
dx_i	+	+	-
$d\theta_i$	-	-	+

3.2.2 Case 3: Decentralized management of fallows

In the absence of any central coordination, farmers have no incentive to weigh foregone externalities as a cost when allocating land between cultivation and fallow. The necessary conditions for profit maximization when farmers fail to internalize the biomass externality are given below.

$$L_{xi} = -q\eta_i h_2^i + pAf_1^i - pA\eta_i f_4^i - c\eta_i - \frac{\mu_i \eta_i}{\overline{X}_i} \le 0, x_i \ge 0, L_{x_i} x_i = 0 \tag{9}$$

$$L_{l_{hi}} = qh_1^i - w \le 0, l_{hi} \ge 0, L_{l_{hi}} l_{hi} = 0 \tag{10}$$

$$L_{l_{ci}} = pAf_2^i - w \le 0, l_{ci} \ge 0, L_{l_{ci}} l_{ci} = 0 \tag{11}$$

$$L_{z_i} = pf_3^i - v \le 0, z_i \ge 0, L_{z_i} z_i = 0 \tag{12}$$

$$L_{\eta_i} = q\left(\overline{X}_i - x_i\right)h_2^i + pA\left(\overline{X}_i - x_i\right)f_4^i - cx_i - \frac{\mu_i x_i}{\overline{X}_i} = r\mu_i - \dot{\mu}_i \tag{13}$$

$$b - \frac{\eta_i x_i}{\overline{X}_i} = \dot{\eta}_i \tag{14}$$

$$\lim_{t\to\infty} e^{-rt}\mu \ge 0, \lim_{t\to\infty} e^{-rt}\mu_i \eta_i = 0 \tag{15}$$

These conditions correspond to the Nash equilibrium solution for the choice of cultivated land, labor, fertilizer, and biomass density. The marginal value of the biomass externality is not weighed in the land allocation decision or in the evolution of the biomass shadow value. Disregarding the externality, farmers prefer to expand the area under cultivation. Farmer welfare under these conditions is necessarily lower due to underprovision of the biomass externality.

Policies to spur an efficient allocation of land between cultivation and fallow include a tax on cultivated land or a subsidy on fallowed land, as well as a subsidy on forest products. In the following cases, I examine second-best options to curtail fallow biomass exploitation, potentially raising the level of social welfare relative to the case of decentralized management under perfect markets.

3.2.3 Case 3: Decentralized fallow management with liquidity constraints

Now I consider a situation in which farmers do not coordinate fallow management but are constrained in their use of purchased inputs by a limited cash budget comprised of credit and off-farm wage income. I introduce a labor market restriction to capture the limited off-farm employment opportunities typical of rural developing country settings. Wage labor is positive when family members work off-farm, but it cannot exceed the employment constraint M. Negative wage labor implies that labor is hired in for agricultural activities, as may be the case during peak periods such as harvesting. I use the equality $L = l_h + l_c + M$, where L represents the household's labor endowment, substituting out l_h to simplify the profit maximization problem. The Lagrangian for this problem becomes

$$L = qh^i\left(L - M - l_{ci}, \theta_i, \overset{N_i}{\underset{j}{\Sigma}} \theta_j\right) + pAf^i\left(x_i, l_{ci}, z_i, \theta_i, \overset{N_i}{\underset{j}{\Sigma}} \theta_j\right) - cx_i\eta_i$$

$$+ \lambda_i\left(R + wM - vz_i\right) + \mu_i\left(b - \frac{\eta_i x_i}{\overline{X}_i}\right)$$

$$L_x = -q\eta_i h_2^i + pAf_1^i - pA\eta_i f_4^i - c\eta_i - \frac{\mu_i\eta_i}{\overline{X}_i} \le 0, x_i \ge 0, L_{x_i} x_i = 0 \tag{16}$$

$$L_{lc} = -qh_1^i + pAf_2^i \le 0, l_{ci} \ge 0, L_{l_{ci}} l_{ci} = 0 \tag{17}$$

$$L_z = pf_3^i - \lambda v \le 0, z_i \ge 0, L_{z_i} z_i = 0 \tag{18}$$

$$L_\lambda = R + wM - vz_i \ge 0, \lambda \ge 0, L_{\lambda_i} \lambda_i = 0 \tag{19}$$

$$L_\eta = -qx_i h_2^i + pA\left(\overline{X}_i - x_i\right)f_4^i - cx_i - \frac{\mu_i x_i}{\overline{X}_i} = r\mu_i - \dot{\mu}_i \tag{20}$$

$$b - \frac{\eta_i x_i}{\overline{X}_i} = \dot{\eta}_i \tag{21}$$

$$\lim_{t\to\infty} e^{-rt}\mu_i \ge 0, \lim_{t\to\infty} e^{-rt}\mu_i\eta_i = 0 \tag{22}$$

The liquidity constraint for input purchases is given by $R + wM = vz$, where R represents access to credit, wM is cash income from off-farm employment (or expenditures for hired labor if M is negative), and λ is the shadow value of loosening this constraint. If the liquidity constraint is nonbinding, the first order conditions mimic those in case 2. If the constraint is binding, purchased inputs are underused relative to the privately optimal amount such that $z_i = \frac{R + wM}{v}$.

Assuming Cobb-Douglas technology, comparative static results are similar to those from case 1, except for the effects of the off-farm wage rate and the credit parameter R. The effect of the off-farm employment constraint is ambiguous because it is not clear whether decreases in fallow or cropped area productivity dominate following decreases in cultivation and harvesting labor. However, the off-farm wage rate has a different effect on production decisions than does the labor constraint. Since the wage rate does not directly determine labor allocation decisions, it affects production only through the liquidity constraint. A higher wage rate thus leads to increased input use and cultivated area and diminished fallow biomass. Unsurprisingly, increased credit also causes expansion of cultivated area and contraction of the fallow biomass as farmers expand crop production at the expense of fallow area.

Table 3.3 Comparative statics with decentralized fallow management and incomplete labor and credit markets (Cobb-Douglas production)

	dM	dw	dR
dx_i	?	+	+
$d\theta_i$	?	-	-

These results provide the basis for considering liquidity constraints a second best policy to minimize inefficiencies caused by decentralized fallow management. I further examine the implications of credit access by deriving its effect on aggregate welfare.

Differentiating the Lagrangian representing social welfare, which is simply the sum of profits over all farms in the sub-watershed, and using the envelope theorem to drop those terms equal to zero according to the necessary conditions for individual profit maximization yields the following expression

$$\left(-p\eta_i \sum_{j\neq i}^{N_i} f_5^j - q\eta_i \sum_{j\neq i}^{N_i} h_3^j\right)\frac{dx_i}{dR} + \left(p\left(\overline{X}_i - x_i\right)\sum_{j\neq i}^{N_i} f_5^j + q\left(\overline{X}_i - x_i\right)\sum_{j\neq i}^{N_i} h_3^j\right)\frac{d\eta_i}{dR} + \left(\frac{p}{v} f_3^i - 1\right)$$

This expression illustrates the ambiguous effect of improved credit access for community-level income. The first two terms are negative and represent the marginal value of the lost externality caused by a slackening of the constraint. The final term is positive and denotes the marginal value of increased input use due to improved credit access. As the constraint slackens, the marginal value of additional inputs approaches zero, while the marginal value of the lost externality remains negative. Thus, although this expression cannot be signed definitively, I expect the first two terms to dominate when the constraint is relatively relaxed. This result implies that a credit constraint, if not too severe, can improve welfare when fallow management is decentralized.

Note that these results are driven by the assumption of productive local externalities to forest fallow. If these externalities are not economically significant, then both centralized and decentralized management of fallows will be efficient and liquidity constraints and transportation costs will necessarily decrease welfare. Constrained input use or decreased marginal output value in this case leads to underexploitation of the fallow biomass relative to efficient use. While fallow biomass may still provide regional or global public goods, such as carbon storage, it is not privately or collectively optimal for farmers to internalize this cost.

3.2.4 Case 4: Decentralized fallow management with uneven liquidity constraints

Here I consider an unevenly applied liquidity constraint. In other words, R + wM is binding for only a subset of farmers. The unconstrained farmers' choices are made according to the conditions given in case 2, while liquidity-constrained farmers' decisions follow the conditions described in case 3.

As in case 3, the liquidity constraint causes some farmers to limit their exploitation of fallow biomass as they cultivate less land due to purchased input shortfalls. Unconstrained farmers choose their land allocations and input use while ignoring the costs of the foregone positive externalities to other farms from fallowing. Hence, their cultivated land area is greater than is socially optimal, while fallow biomass is overexploited. This lower level of fallow biomass reduces constrained farmers' profits. However, unconstrained farmers are not necessarily worse off than they would be under the efficient management regime described in case 1, thanks to the higher level of biomass maintained by constrained farmers. In the extreme case in which a liquidity constraint forces all other farmers in the locality to maintain the socially efficient level of biomass, the unconstrained farmer's profits are actually higher than they would be under collective or central fallow management.

While unconstrained farmers reap most of the benefits of the liquidity constraint, constrained farmer welfare may actually improve as well if the subset of constrained farmers is large enough to increase the local biomass stock. This result is similar to the ambiguous effects of inequality on common property resource management efficiency found by Baland and Plateau (1997, 1998). In their study, unequal credit constraints may lead to increased efficiency under unregulated commons, though in their fisheries example the unconstrained agents, who garner a larger share of the profits, internalize a larger portion of the externality. This type of result may ensue for fallow management if credit access increases with land endowment. However, ranking the welfare of aggregate, constrained, and unconstrained farmers under the different scenarios is difficult without assuming specific parameter values for the size of the liquidity constraint and the numbers of constrained and unconstrained farmers.

As seen in the comparative static results from case 1, farmers' choices of cultivated land and fallow biomass vary with the fallow on nearby farms, though the direction of the effect is ambiguous. Therefore, farmers may choose the level of cultivated land and fallow strategically, anticipating neighboring farms' fallow management. If the crop production externality dominates the forest product externality, farmers will decrease their own fallow biomass to take advantage of their neighbors'. This behavior will exacerbate the effects of unequal liquidity, causing constrained farmers to conserve more fallow in response to the overexploitation of unconstrained farmers, and vice versa. However, if the forest product externality is more important, then strategic behavior may raise social welfare by spurring both constrained and unconstrained farmers to set aside more land to fallow.

These stylized scenarios illustrate the importance of institutional conditions, as well as prices and ecological parameters, on the exploitation of fallow even under secure property rights. Cases 3 and 4 present plausible, though obviously simplified, scenarios to explain the persistence of fallow under conditions like those found in the Zona Bragantina, where farmers have some access to land and labor markets but may underexploit fallow biomass relative to the privately optimal level due to liquidity constraints limiting the use of soil-enhancing inputs.

By using a continuous model to represent shifting cultivation dynamics, my results do not capture the adjustment costs inherent in a shift to a longer fallow period. Since biomass accumulates gradually, the gains in productivity from a longer fallow will take up to a full cycle to materialize. In the meantime, the reduced income from cultivating a smaller area is costly in the short-term. Thus, even if parameter changes favor increases in fallow length and reductions in cultivated area, the adjustment costs may be prohibitive.

In the following chapters, I confront the empirical issues raised in this discussion. In Chapter 4, I estimate production functions with data from the Eastern Amazon's Zona Bragantina to determine the magnitude of the returns to fallowing in shifting cultivation and forest product harvesting, both private and public. I test whether fallow biomass provides economically significant externalities to farm production, which will better enable me to evaluate the implications of potential market failures for fallow management.

I examine whether farmers behave strategically in response to their neighbors' land use in Chapter 5. The theory predicts the direction of the effect to be ambiguous; however, the dominance of crop production in the Zona Bragantina suggests that farms may be likely to reduce their on-farm fallow in response to additional fallow land on their neighbors' farms, leading to negative spatial correlation in fallow. I estimate the effect of neighbors' fallow on on-farm fallow area using a spatial econometric model. The coefficient on the spatial lag of fallow indicates whether farmers respond to their neighbors land use.

I then test the hypothesis that liquidity constraints affect fallow management in Chapter 6. Fallow management under limited access to liquidity or markets in the presence of externalities may entail underexploitation of the fallow biomass relative to the private but not necessarily social optimum. Thus, the coexistence of market failures and externalities opens the possibility that the underexploitation of fallow by constrained farmers may lead to greater social welfare.

4 Empirical analysis: valuing forest fallow resources and externalities in shifting cultivation

4.1 Data

Data 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 the Zona Bragantina were chosen for study to capture regional variation in distance to commercial centers, agricultural intensification, and rainfall (Mendoza 2004). In late 2002, 271 households in 22 villages were randomly selected and surveyed.

Table 4.1 Household variables

	Mean (Standard deviation)	Observations
Farm size (ha)	40.73 (47.97)	271
Household size (members)	6.18 (2.78)	271
Own farmland (legal title) 1 = yes, 0 = no	0.65 (0.48)	271
Household head education (years)	3.77 (2.91)	271
Use extension services 1 = yes, 0 = no	0.24 (0.43)	271
Use of commercial credit (from bank or cooperative) 1 = yes, 0 = no	0.31 (0.46)	271
Own car 1 = yes, 0 = no	0.09 (0.28)	271
Own television 1 = yes, 0 = no	0.60 (0.49)	271
Use electricity 1 = yes, 0 = no	0.62 (0.49)	271
Own firewood stove 1 = yes, 0 = no	0.85 (0.36)	271
Own gas stove 1 = yes, 0 = no	0.84 (0.37)	271

The survey collected information on demographics, on- and off-farm income, farm and household assets, commercial credit use, and land use, including area under cultivation, pasture, and fallow. Table 4.1 presents the mean values for selected household-level characteristics.

Most of the households are considered smallholders by Brazilian standards, with mean landholdings of 40 hectares[7]. Close to two-thirds of farmers hold legal title to their land. Despite secure land tenure as an asset, only 31% of farms received credit from a commercial bank or agricultural cooperative during the past decade. Sixty-two percent of farms use electricity, indicating a lack of access to infrastructure by some households.

Sampled households are poor even for Pará, earning B$1625 per capita annually, compared to the state average of B$3804 (Verner 2004). Close to two-thirds of income is earned from farm activities, while 37% comes from off-farm sources. Old-age pensions comprise the bulk of off-farm earnings and are received by 39% of households. Annual crops, produced by 90% of the farmers, dominate farm activities, contributing 54% to farm income on average. Perennial crops are produced by 46% of households and make up 24% of farm income. The remainder of farm income includes forest product harvests (14%) and animal products such as eggs, dairy products, and meat (8%). Most farms are semi-commercialized, retaining some produce for home consumption and selling the remainder in regional markets. Farmers sell 65% of perennial and horticultural output, while only marketing 40% of the staple food crops cassava, maize, rice, and beans and 26% of forest products. Table 4.2 reports mean values for each type of output and income source, and Table 4.3 presents output and input prices in the region.

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[7] Ninety-four percent of the farmers' landholdings are 100 hectares or less, the common definition for smallholders in Brazil.

Table 4.2 On- and off-farm income sources

	Mean (Standard deviation)	Observations
Total income ($B[8])	8666 (13280)	271
Annual crop income ($B)	2255 (3751)	271
Perennial crop income ($B)	2826 (10783)	271
Produce perennial crops 1 = yes, 0 = no	0.46 (0.50)	271
Forest product value ($B)	666.94 (3206.31)	271
Harvest fallow products 1 = yes, 0 = no	0.69 (0.46)	271
Animal product income ($B)	267 (1017)	271
Off-farm income ($B)—agricultural and non-agricultural wage	1040.04 (2112.50)	271
Off-farm income ($B)—scholarships and remittances	117 (336)	271
Off-farm income ($B)—pensions	1494 (4009)	271
Farms with wage income 1 = yes, 0 = no	0.52 (0.50)	271
Farms with non-wage income 1 = yes, 0 = no	0.56 (0.50)	271

Table 4.3 Output and input prices and transportation costs

	Mean (Standard deviation)	Observations
Village-level annual price index ($B/kg)	0.81 (0.23)	271
Village-level perennial price index ($B/kg)	3.26 (1.81)	271
Forest product price ($B/kg)[9]	6.57 (14.76)	187
Village-level fertilizer price index ($B/kg)	0.93 (0.10)	271
Agricultural wage rate ($B/day)	8.26 (1.38)	271
Transportation cost ($B/kg)	0.01 (0.01)	271
Transportation frequency	3.86	271

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[8] US$1 = $B 2.97, 2002 average

[9] I impute forest product prices for households that do not collect forest products using village averages.

1 = 1x/week, 2 = 2x/week, 3 = 3x/week, 4 = 1x/day, 5 = >1x/day	(1.37)	
Distance from household to market (km)	23.68 (12.41)	252

Comprehensive farm-level data on forest fallow for the entire Zona Bragantina would be ideal to estimate the off-site flow of benefits and their spatial scale but are unavailable. I make use of the household survey data on land use among the sampled farms as one solution. As an additional approach to address this gap, I turn to GIS (geographic information systems) data on forest cover, using the MODIS Vegetation Continuous Fields (VCF) to construct an alternative measure of external fallow. The VCF data consist of 25 hectare (0.25 km^2) resolution pixels created using 40 day composite satellite images from March 2001-March 2002 (Hansen et al. 2003)[10]. Each pixel represents percent canopy cover, defined as the amount of sunlight blocked by tree canopies over five meters high. Figure 2 gives 2001-02 tree canopy cover for the Zona Bragantina.

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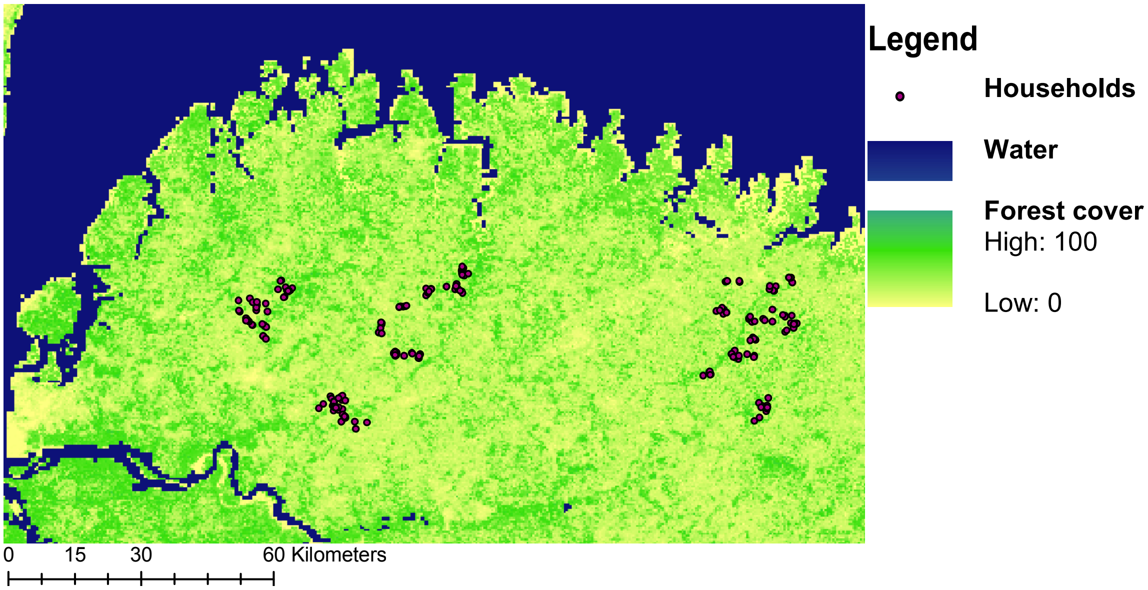
[10] The 2001-02 VCF data provide the closest available estimates of forest cover during the 2001-2002 cropping season. Twenty-five hectare pixels are a sufficiently fine measure of tree cover relative to the size of landholdings among the surveyed farmers, as the median farm size is also 25 hectares. The percent canopy cover approximates both the area and density of forest cover, since the share of land with five-meter tree cover is likely to be highly correlated with vegetation density.

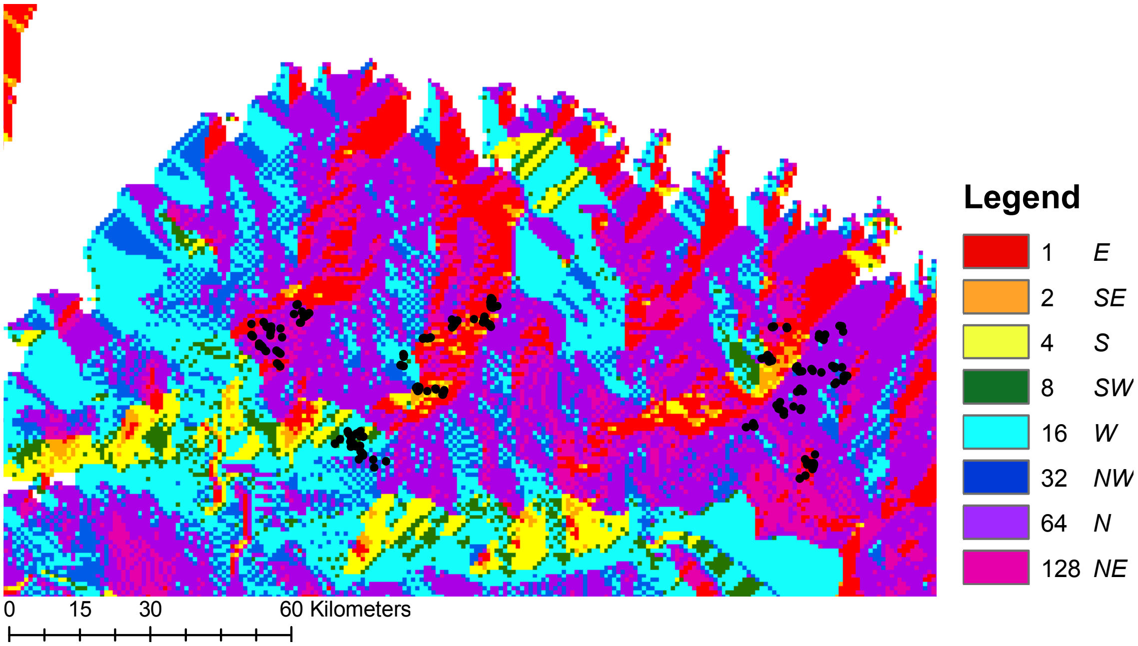
Figure 2 Tree canopy cover in the Zona Bragantina, March 2001-March 2002



Source: Hansen, DeFries, Townshend, et al. 2003

I also use GIS flow direction data from the US Geological Survey to determine where farms lie along a gradient from upstream to downstream in relation to one another. Knowledge of farms' relative positions within the sub-watershed is essential for defining the upstream forest cover variables. According to a flow direction map for the region (Figure 3), 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 observations affect farms downstream and are affected by farms upstream. I discuss the construction of the external forest fallow variable further later in the chapter. The US Geological Survey also provides slope data for the region at 1-km resolution.

Figure 3 Flow direction in the Zona Bragantina



Source: U.S. Geological Survey

4.2 Empirical approach

My approach to valuing the services provided by on-farm and off-site forest fallow involves estimating production functions for two primary activities in the Zona Bragantina: crop production and forest product harvesting[11]. The surveyed farmers produced a total of 50 annual and perennial crops, with cassava, maize, beans, and black pepper among the most common. Collecting forest products makes a modest contribution to income relative to cropping but is practiced widely among the surveyed farms. The production function estimations allow me to measure the contribution of on- and off-farm fallow to productive activities and test for positive externalities to fallowing in each. I also calculate the contribution of fallow resources to total farm income by aggregating the respective contributions of on-farm and upstream fallow to cultivation and forest products. I use an instrumental variables approach in both estimations to address issues of measurement error, omitted variables, and simultaneity, which I discuss below. I also account for potential spatial dependence in the error terms of these equations by estimating spatially-correlated error models.

4.3 Crop production function

The dependent variable in the crop production function is the log of crop output value, with different commodities aggregated using average output prices in the region. Although farms commonly reserve some crops for home consumption in the region, market prices provide appropriate values for these commodities since 97% of sampled farmers sell at least some of their produce. I employ a Cobb-Douglas specification for cropping technology. Output is modeled as a function of cultivated land area, family and hired labor, fertilizer, on-farm fallow area, and off-farm (upstream) fallow area. Because farm 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 (Maler 1991). The crop value equation can be represented as follows:

$$\ln y_i = \beta_o + \beta_1 \ln f_i + \beta_2 W_1 \ln F + \beta_3 \ln X_i + \beta_4 H_i + \varepsilon_i$$
$$\varepsilon_i = \lambda W_2 \varepsilon + u_i$$

In this specification, y_i represents the i^{th} farm's crop value. Fallow area is represented by f_i, while F is a vector of all farms' fallow area. Cultivated land area, family and hired labor, and fertilizer are represented by X_i, a vector of conventional inputs.

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[11] Ranching and livestock products make up the remainder of agricultural activities. Ranching is less common in the Zona Bragantina than either cropping or forest product collection. Pasture is found on only 28% of farms, comprising 5% of farm land on average among the entire sample.

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 autoregressive model accounts for the fact that unobserved variables subsumed by the error term may be correlated based on distance between households, allowing for efficient estimation of the parameters (Dubin 1998). The strength of the 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 gives equal weight to neighbors upstream of each farm to capture the hydrological externalities of local forest fallow. 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. Thus, $W_1 \ln F$ represents a weighted average of off-farm fallow area upstream of each observation. I also refer to this term as a spatial lag of the fallow variable.[12]

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 proposed spatial weighting matrices is thus justified conceptually, and it ensures that the spatial autoregressive

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[12] Following the convention used by Anselin (1988) and others, I use the term spatial lag to mean a weighted sum of neighboring or contiguous values of the variable of interest, somewhat analogous to the concept of temporally-lagged variables in time-series analysis. Since the data vary only over space, not time, no temporal lags are used in any of the analyses in this paper. Spatial lag models generally refer to spatial correlation in the dependent variable, while spatial error models account for spatial autoregressive processes in the disturbance.

parameters can be identified[13]. However, if spatial correlation among the disturbances does in fact follow the same pattern as the hypothesized hydrological externality, then the two 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. The household head's schooling years and binary variables indicating use of extension services and land ownership may help control for farmer management skills[14]. A binary variable for perennial crop production controls for the higher prices perennial crops command in regional markets relative to annual crops[15]. Land quality indicators include farmer-reported dummy variables for black clay and charcoal-enriched soil ("*massape*" and "*preta*," both favorable types) and poor soil ("*arisca*") and GIS data on slope, which indicates 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. However, they do not adequately indicate land-use history, a major determinant of soil quality in the region (Tucker et al. 1998). The equation also includes municipality dummies. Table 4.4 reports the mean values for the variables used in the production function estimation.

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[13] As shown by Anselin 1988 (pp. 84-85), spatial lag and spatial error parameters are generally not identified without nonlinear restrictions when the two weighting matrices are the same.

[14] I also included the log of the household head's age in an early regression but dropped it in subsequent analyses because of missing observations and lack of significance. Inclusion of this variable did not qualitatively affect the other parameter estimates.

[15] 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 crop output and perennial production equations are independent (p = 0.86-0.88, depending on the measure of off-farm fallow used), so I treat perennial production as exogenous in the regressions that follow. Perennial crops can be grown in soil conditions found throughout the Zona Bragantina. However, farmers with facing higher rainfall, better access to extension services, and those less averse to price risks are more likely to produce perennials (Borner 2005).

The primary parameters of interest are the coefficients of on-farm fallow and external fallow. The coefficients of on-farm and external fallow give the respective output elasticities, indicating the contribution of these fixed environmental factors to crop production. I tackle the hypothesis that local forest cover provides positive externalities to downstream farms by testing whether the coefficient of the spatially-weighted external forest fallow variable is significantly greater than zero.

Table 4.4 Production function variables

	Mean (Standard deviation)	Observations
Crop output value ($B)	5118.27 (11972.62)	261
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
On-farm fallow area (ha)	22.60 (28.97)	271
No on-farm fallow land 1 = yes, 0 = no	0.14 (0.35)	271
Off-farm (upstream) average fallow area – survey data (ha/upstream neighbor)	24.54 (19.62)	236
No upstream fallow area 1 = yes, 0 = no	0.03 (0.16)	236
Off-farm (upstream) canopy cover – GIS data, 3km radius (% area)	30.10 (6.23)	261
No upstream canopy cover 1 = yes, 0 = no	0 (0.00)	261
Slope (degrees)	2.65	261

	(2.54)	
Black clay (*massape*) soil	0.10	271
1 = yes, 0 = no	(0.30)	
Charcoal enriched (preta) soil	0.10	271
1 = yes, 0 = no	(0.31)	
Poor (*arisca*) soil	0.06	271
1 = yes, 0 = no	(0.24)	

4.3.1 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[16]. Fallow area has the additional advantage of proxying for any flows of hydrological or crop pollination services provided by forest fallow within the farm.

As mentioned previously, I employ two alternative measures of off-farm fallow. I define a variable using the household survey data to measure the average area under forest fallow upstream of each farm, using the spatial weighting matrix W_1 to define which farms are considered neighbors. I also generate a GIS fallow variable using the VCF data measuring percent canopy cover, again using each farm's location to determine the upstream forest area to extract.

I define the externality-relevant neighborhood for each household based on the scale and direction of forest ecosystem services discussed in the ecological literature. Hydrological research suggests that regulation of soil water and flooding by forests is

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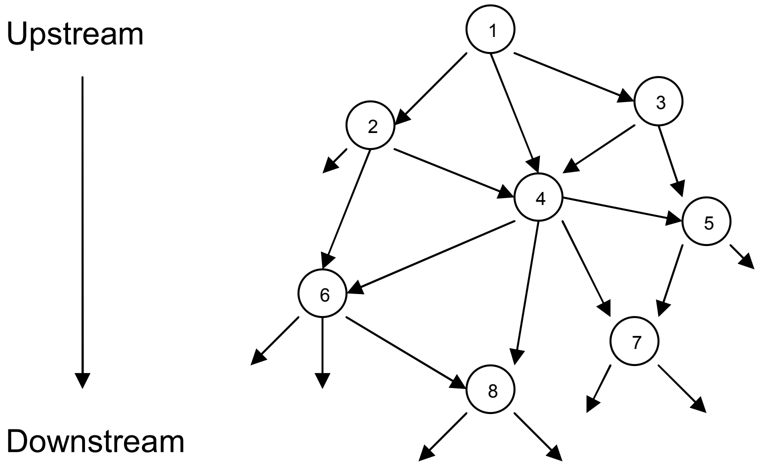
[16] In the biomass density growth function proposed by López (1993) and used in the theoretical model in Chapter 3, a smaller fraction of land under cultivation entails longer fallow periods on average and hence more biomass accumulation because land is regularly rotated between cropping and fallow. 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. The steady state assumption may be plausible in the conditions of the Zona Bragantina, where current agronomic practices have been largely in place and minimal migration has occurred for the past several decades, in contrast to much of the

quite localized; larger-scale forest externalities are possible but remain understudied (Bruijnzeel 2004). Crop pollination services also occur on a small scale of 1-3km (Ricketts et al. 2004, Kremen et al. 2004).

For the survey-derived fallow area variable, I count every observation upstream of a farm within a common drainage area as a neighbor, using flow direction data to determine the relative positions of farms. Those farms furthest upstream within a locality are thus assumed to affect all downstream farms; however, they have no neighbors among the sampled farms and so must be excluded from the final crop value equation testing for externalities. Figure 4 illustrates the geographic structure of the relationship. Land use on farm 1 affects all farms downstream, but I have no information on land use upstream of farm 1. Meanwhile, farm 8 is affected by land use on farms 1-7 in its position as the farthest observation downstream.

Figure 4 Flow direction of hypothesized hydrological externalities



Using the GIS canopy cover data, I cannot extract upstream forest cover within each drainage area individually for each farm, so I instead extract a wedge-shaped

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Brazilian Amazon. López (1997) also finds similar output elasticities of fallow using biomass volume and neighborhood upstream of each farm with a radius of 3 km. As expected, the survey- and GIS-derived variables are positively correlated at the 3-km radius scale (rho = 0.42).

Deriving the off-farm fallow variable using the survey data ensures that on- and off-farm fallow are measured the same way and prevents overlap between the two variables, both attractive features. This variable represents upstream forest cover accurately if the sampled farms are representative of other farms within the same neighborhood. Conversely, the GIS canopy cover data offers the advantage of covering the Zona Bragantina region comprehensively rather than being limited by the survey sample size. It can also measure upstream forest cover data for all farms for which I have GIS coordinates, while the survey data gives no information about upstream land use for farms with no upstream neighbors among sample[17]. However, the GIS variable cannot avoid some overlap with the on-farm fallow variable even though I exclude the pixel matching the farm's location, since data on the exact mapped boundaries of each farm are unavailable[18]. In addition, canopy cover proxies for fallow biomass as well as area, so this variable may be correlated with on-farm biomass. With these drawbacks in mind, I use both measures in my analysis to enhance the robustness of the results. Both approaches define the externality at the farm level, allowing for more variation in the off-farm forest cover variable compared to other studies that define the forest externality at the village or sub-watershed level (e.g., López 1993, 1997, 1998; Pattanayak and Kramer 2001; Pattanayak and Butry 2005).

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fallow area as alternative measures in Ghana.

[17] GIS coordinates are missing for 10 farms in the sample, which are excluded from the analysis. In addition, 35 farms (13% of the sample) have no upstream neighbors as defined using the household survey data and are excluded from regressions that incorporate this variable.

[18] To avoid counting farms as their own neighbors, I exclude the farm from the calculation of the household survey-derived off-farm fallow variable, and I exclude the pixel most closely matching the farm's location from the GIS forest cover variable.

4.3.2 Econometric issues

Several potential sources of endogeneity are causes of concern in obtaining consistent estimates of the parameters of interest. Factors such as land quality and farm management ability cannot be fully controlled for and may be correlated with yield and fallowing practices, as well as other inputs, causing omitted variable bias. In particular, poor soil quality may spur farmers to allocate more land to fallow while also depressing yields, biasing the on-farm fallow coefficient downward. Soil quality may be spatially correlated, leading to a possible downward bias on the external forest fallow coefficient as well.

Measurement error of fallow variables, which proxy for but do not exactly measure fallow biomass, may cause attenuation bias, further lowering the elasticity estimates (Greene 2000). In addition, differing measurement error between the on-farm fallow area and off-farm GIS canopy cover variable may also be a source of bias due to the different data sources used to construct them. The GIS canopy cover data indicates fallow biomass density as well as area, while the on-farm fallow measure only incorporates fallow area (though as mentioned previously, fallow area and biomass are likely to be correlated). Thus, the coefficient of on-farm fallow may be biased downward and the coefficient of GIS canopy cover upward if external canopy cover is correlated with on-farm biomass density. However, the survey-reported data on off-farm fallow area avoids this source of bias.

Finally, the coefficients of cultivated area, labor, fertilizer, and on-farm fallow may be biased upward if the farmer chooses input and output levels simultaneously. Off-farm fallow is less likely to be vulnerable to simultaneity problems since the farmer does not determine fallow levels on neighboring farms, though it may still be affected by climatic shocks experienced by all farms within a neighborhood. The error term in the production equation thus encompasses not only white noise, but also measurement error, agroecological conditions, farmer intentions, and other factors that are unaccounted for in the data.

4.3.3 Identification strategy and instrumental variables approach

While I cannot cleanly solve the identification problem with the data at hand, I employ several strategies in an effort to consistently estimate the parameters of interest. As discussed above, I include several observed indicators of land quality and management ability, including slope, farmer-reported soil types, use of extension services, and the household head's education level. Modeling spatial correlation in the error terms based on distance between farms also helps control for unobserved patterns in agroclimatic factors and farmer knowledge over space[19]. Finally, I use an instrumental variables (IV) estimator to address potential remaining omitted variables and measurement error issues.

To address the endogeneity of on- and off-farm fallow using IV, I need at least two instruments highly correlated with these factors but uncorrelated with the residual of the crop output equation. As discussed by Heckman (1991), the effects of past experiences or decisions on outcomes can be hard to disentangle from underlying heterogeneity, making identification of truly exogenous variables challenging, if not impossible. I use the log of farm size, forest product prices, and binary variables

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[19] Mardia and Marshall (1984) show that the maximum likelihood estimator of the spatial error model is consistent if the domain or observation area of the data increases as the sample size increases (domain asymptotics). The consistency of the maximum likelihood estimator has not been shown when the sample size increases under a fixed domain, causing an increase in the density of observations within the given region (infill asymptotics) (Cressie 1993). Therefore, consistency of the spatial errors estimators discussed in this paper applies only under increasing domain asymptotics.

indicating ownership of a firewood stove and ownership of a gas stove to instrument for on-farm fallow. Farm size affects the amount of land available for fallowing and so is likely to be a strong predictor of fallow area. In addition, farm size has no direct effect on crop output because cultivated land area, clearly a crucial factor of production, is included directly in the production function, making total farm area unrelated to crop value and hence a valid instrument. I expect forest product prices and firewood stove ownership to be positively correlated with on-farm fallow since fallow land typically serves as a source of forest products for sale or home consumption, with firewood the most common product. Conversely, gas stove ownership may negatively affect on-farm fallow by decreasing the household's dependence on firewood fuel. Forest-product price is a good instrument because it is unlikely to be correlated with unobservable factors affecting crop output mix and yields despite its impact on the marginal returns to fallow area. Firewood and gas stove ownership have similar advantages as instruments unless farmers invest in stoves based on their planned allocation of land to fallow.

To instrument for off-farm fallow, I use the spatially-lagged values of the on-farm fallow instruments and of other household-level exogenous variables included in the crop production equation. Thus, the instruments include the spatial lags of the log of farm size, forest product prices, firewood and gas stove ownership, and other household and agroecological characteristics expected to affect crop production. The spatially-lagged values of farm and household 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[20].

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[20] I also tested the exogeneity of all inputs jointly, including cultivated area, labor, and fertilizer. I added the log of family size and the share of males age 16-65 as instruments in this regression. I could not reject

I do not use the spatially-lagged values of conventional inputs or the perennial production indicator due to concerns about the potential endogeneity of these variables. I use the same spatial weighting matrix to construct the instrumental variables as that used to construct the lagged fallow variables to ensure that neighbors' fallow area is regressed on the characteristics of these same neighbors. While this strategy may fall short of approaches that use experimental or panel data to identify the parameters of interest, it still has potential to shed some light on the relationship between fallow biomass and agricultural productivity.

The IV approach performs well, as the instruments are both strong predictors of on- and off-farm fallow and are uncorrelated with crop value. First-stage regressions for the on- and off-farm fallow variables are presented in the Appendix (Table B1). The exogenous variables explain a high proportion of the variation in on-farm fallow, upstream fallow area, and upstream canopy cover as indicated by R-squared statistics of 0.74-0.75, 0.91, and 0.76, respectively. The log of farm size is very highly correlated with on-farm fallow across both specifications (p = 0.00). Forest product prices also significantly predict on-farm fallow (p = 0.05) in one of the first-stage equations for on-farm fallow (column 3). Spatially-lagged values of farm size, forest product price, gas- and firewood-stove ownership, and black clay soil have strong effects on upstream fallow area (column 2). Similarly, lagged log farm size, firewood stove ownership, use of extension services, farm ownership, charcoal-enriched soil, and slope help explain GIS canopy cover within a 3-km upstream radius of each farm (column 4).

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exogeneity of all inputs jointly (p = 0.76-0.96, depending on the off-farm fallow variable). In the remaining discussion, I focus on controlling for endogeneity of the fallow variables.

The Sargan test for overidentification indicates that the instrumental variables as a group are uncorrelated with the residuals of the output equations[21]. I also checked the validity of the instruments individually by including each one-by-one in the IV estimation of crop value (Table B2). None were significant at conventional levels. The p-values for the log of farm size, forest product price, firewood-stove ownership and gas-stove ownership ranged from 0.21-0.94, and p-values for the spatially-lagged variables ranged from 0.16-0.99 across both models.

While the IV estimates are consistent, a Hausman test could not reject exogeneity of the on- and off-farm fallow variables, whether using the survey or GIS measures of off-farm fallow (p= 0.55-0.87). Thus, the least squares estimates of the elasticities of on- and off-farm fallow are both consistent and more efficient than the IV estimates.

4.3.4 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 according to the household survey data (Table 4.4). 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 (Soloaga 2000). Instead, I deal with non-essential inputs according to the approach outlined by Battese (1997), adding dummy variables to indicate non-use of each input[22]. In addition, ten farms produce no outputs during the season and are excluded from the crop production equation.

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[21] IV validity tests were carried out assuming uncorrelated (non-spatial) disturbances.

[22] Battese represents a two-input Cobb-Douglas production technology using two equations, assuming that one input, x1, is used by all firms, and a second input, x2, is used by only some firms:

ln y = b0 + b1*ln x1 + b2*ln x2 + u, for all farms with x2>0

4.3.5 Results

Table 4.5 presents four sets of estimates of the crop production function. The first two columns report estimates from the spatial error model (SEM) (1) and from the spatial error model with instrumental variables (SEM-IV) (2) using survey-reported off-farm fallow area to represent upstream fallow. The last two columns show SEM (3) and SEM-IV (4) estimates with the GIS canopy cover variable as an alternative measure of upstream fallow. As stated above, the on- and off-farm fallow variables can be considered exogenous, so all four sets of elasticity estimates are consistent. All models have a satisfactory fit, as indicated by R-squared statistics of 0.56-0.60, 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 crop output.

Comparisons among the four models reveal that on-farm and upstream fallow are both important factors of crop production in the Zona Bragantina. The elasticity of on-farm fallow is positive across all models and significantly different from zero in three of the four models, varying from 0.10-0.17. The IV estimates (Models (2) and (4)) are higher than those from the regular spatial errors models (Models (1) and (3)), supporting the intuition that unobservable land quality differences and measurement error may bias the estimates of fallow elasticity downward, though formal tests could not reject

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$\ln y = a0 + b1*\ln x1 + u$, for all farms with $x2=0$

The two equations can be pooled to write

$\ln y = b0 + (a0-b0)*D + b1*\ln x1 + b2*\ln z + u$

where D is a dummy variable indicating non-use of x2 and $z = \max(D,x2)$. This strategy assumes a constant parameter b1 and error u across both equations.

exogeneity of on-farm fallow. These estimates suggest that own-fallow land makes a substantial contribution to crop output, close to that of hired labor or fertilizer.

Table 4.5 Crop production function estimation

	SEM[23] (1)	SEM-IV (2)	SEM (3)	SEM-IV (4)
Log on-farm fallow area	0.098*	0.125	0.099*	0.174*
	[0.058]	[0.078]	[0.059]	[0.091]
Log off-farm fallow – upstream survey fallow area	0.366**	0.378**		
	[0.158]	[0.184]		
Log off-farm fallow – 3 km upstream GIS canopy cover			0.964**	0.458
			[0.470]	[0.755]
Log cultivated area	0.414***	0.405***	0.442***	0.434***
	[0.099]	[0.101]	[0.095]	[0.096]
Log family labor	0.128	0.126	0.068	0.075
	[0.093]	[0.094]	[0.089]	[0.089]
Log hired labor	0.175***	0.172***	0.187***	0.170***
	[0.065]	[0.066]	[0.061]	[0.062]
Log chemical fertilizer	0.146***	0.146***	0.169***	0.160***
	[0.055]	[0.056]	[0.056]	[0.058]
Perennial producer (binary)	0.911***	0.914***	0.835***	0.833***
	[0.177]	[0.178]	[0.166]	[0.167]
Use extension services (binary)	0.262	0.27	0.21	0.212
	[0.177]	[0.178]	[0.165]	[0.167]
Household head schooling years	-0.018	-0.018	-0.022	-0.021
	[0.025]	[0.025]	[0.024]	[0.024]
Farm owner (binary)	0.07	0.07	-0.027	-0.016
	[0.157]	[0.158]	[0.149]	[0.150]
Black clay soil (binary)	0.221	0.227	0.204	0.186
	[0.236]	[0.238]	[0.235]	[0.237]
Charcoal-enriched soil (binary)	0.373*	0.381*	0.378*	0.417*
	[0.215]	[0.216]	[0.216]	[0.220]
Poor soil (binary)	-0.122	-0.125	0.134	0.088
	[0.309]	[0.310]	[0.282]	[0.288]
Slope	-0.011	-0.013	-0.018	-0.012
	[0.027]	[0.027]	[0.027]	[0.029]
Castanhal municipality (binary)	0.25	0.251	0.606**	0.476*
	[0.228]	[0.229]	[0.246]	[0.288]
Igarapé Açu municipality (binary)	0.281	0.277	0.299	0.249
	[0.229]	[0.233]	[0.216]	[0.221]
No on-farm fallow (binary)	0.429	0.495	0.530**	0.683**
	[0.285]	[0.323]	[0.264]	[0.311]
No upstream fallow area (binary)	1.102*	1.131*		

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[23] All regressions estimated in Stata 8 unless otherwise noted

	[0.602]	[0.657]		
No family labor (binary)	1.260*	1.243*	0.844	0.873
	[0.651]	[0.653]	[0.647]	[0.651]
No hired labor (binary)	0.018	0.013	0.128	0.059
	[0.284]	[0.285]	[0.270]	[0.275]
No fertilizer (binary)	0.174	0.157	0.302	0.273
	[0.308]	[0.312]	[0.301]	[0.304]
Constant	3.343***	3.202***	1.323	2.905
	[0.732]	[0.758]	[1.703]	[2.597]
Spatial error correlation coefficient (λ)	-0.033	-0.055	-0.007	-0.020
	[0.138]	[0.142]	[0.181]	[0.147]
Observations	228	228	251	251
R-squared	0.60	0.60	0.57	0.56
Log likelihood	-313.83	-314.36	-349.64	-350.78

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

The elasticity estimates are similar in magnitude to those from other econometric and agronomic studies. For instance, López (1993, 1997, 1998) finds the village-level fallow biomass factor share to vary between 0.15 and 0.2 in Ghana and Cote d'Ivoire. Mendoza (2004) uses the same data set as the present study to estimate the contribution of fallow length to plot-level cassava profits, finding an output elasticity of 0.22. An Altamira, Pará, field study finds the elasticity of maize yields with respect to fallow age to be 0.33 (Silva-Forsberg et al. 1997). An agronomic study from the Zona Bragantina showed rice yields to improve by 10-44% as fallow age increased from four to ten years, corresponding to a fallow elasticity of 0.07-0.29, with the lower elasticities found on fields to which fertilizer was applied (Kato et al. 1999). The wide use of fertilizer by sampled farms may help explain why the elasticities estimated in this study fall in the lower range of previous studies.

The estimated elasticity of off-farm fallow in crop production is also positive across all four estimates, providing evidence that upstream forest fallow improves productivity for downstream farms. The actual elasticity estimate varies considerably based on the estimator used. Models (1) and (2), which use survey-reported fallow area as the measure of upstream fallow, show a significant and positive elasticity of 0.37-0.38. In Model (3), which employs the GIS canopy cover variable to measure off-site fallow, the elasticity jumps to 0.96. 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 IV estimate of upstream canopy cover in Model (4) drops to 0.46, much closer in magnitude to the elasticities from Models (1) and (2), though not significantly different from zero. The magnitude of the externality effects estimated in Models (1) and (2) 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 (Pattanayak and Butry 2005).

Although the limitations of cross-sectional, non-experimental data make obtaining precise parameter estimates difficult, the findings indicate that farms with more fallow both on-farm and upstream generally reap higher output yields, providing support for the hypothesis that neighbors' forest fallow provides positive externalities to crop production. I return to the discussion of forest fallow externalities after estimating the forest product equation later in this chapter.

4.3.6 Resampling and robustness analysis

I carry out a number of robustness checks to ensure that the estimated elasticities of on- and off-farm fallow are indeed positive across different sub-samples of farmers. Table B3 reports least squares estimates of the crop production function when farms in the lowest and highest tenth percentiles of on-farm fallow area are excluded from the analysis (columns 2 and 3). Columns 4 and 5 exclude farms with the highest and lowest tenth percentiles of off-farm fallow area. Table B4 repeats the exercise, using GIS canopy cover as the measure of upstream fallow. The results show that the coefficient of on-farm fallow is relatively stable when farms at the tails of the distributions of the fallow variables are excluded from the regression, varying between 0.08-0.11. Upstream fallow area is less robust, though still high in magnitude, ranging from 0.20-0.51. The higher and statistically significant elasticity is estimated when the top tenth percentile of the sample is dropped. Thus, the results on fallow externalities are driven particularly by farms that lie downstream of relatively less forested areas. The elasticity of GIS canopy cover varies from 0.92-1.14 and is significantly different from zero in both sub-groups, indicating that the estimates are robust.

Figures B1 and B2 show on-farm and upstream fallow elasticities with 95% confidence intervals when each observation is dropped one-by-one in a leave-one-out cross-validation procedure (LOOCV; see, e.g., Stone 1974, Geiser 1975. Figures B3 and B4 repeat the exercise for on-farm fallow and upstream canopy cover. The elasticity estimates fall within a similar range as those estimated when dropping the top and bottom tenth percentiles: 0.07-0.12 for on-farm fallow, 0.30-0.43 for upstream survey-reported fallow area, and 0.82-1.07 for upstream GIS canopy cover. Averaging the results of the LOOCV gives elasticities of 0.099 and 0.367 for on-farm and upstream fallow area (Model 1) and 0.099 and 0.966 for on-farm fallow and upstream canopy cover (Model 3), all very close to the SEM estimates reported in Table 4.5

Finally, the bootstrap bias estimates of on- and off-farm fallow elasiticicities from the four models calculated using 500 replications indicate that the finite sample biases are small relative to the sizes of the parameter estimates (Table B5).

As an additional verification that forest cover provides hydrological externalities, I also estimate all four specifications of the crop production function including downstream forest cover as an additional regressor. If forest cover provides positive hydrological externalities, then upstream forest cover will affect crop production but downstream forest cover will not. Table B6 presents the results of these regressions. Across all four models, downstream forest cover has no significant effect on crop value, in contrast to the elasticity of upstream forest cover. In fact, the coefficient on downstream forest cover is negative in Models (1) and (2) and is very small in magnitude in Models (3) and (4). These findings support the contention that forest cover improves crop output by regulating floods and soil moisture, and that other potential non-hydrological services such as crop pollination do not drive the results.

4.3.7 Other factors of production

Elasticity estimates for the remaining inputs are largely positive and significantly different from zero across all four specifications. Cultivated area makes the most substantial contribution to crop output, with an elasticity of 0.41-0.44. Hired labor and fertilizer are also important, supplying 16-18% and 11-14% of crop output, respectively. Production of perennial crops, which command higher market prices than annuals, raises output value considerably. Agroecological variables are also important in determining output value—black clay and charcoal-enriched soils boost output, while poor soils and steeper slopes dampen it, though only the effect of charcoal-enriched soil is statistically significant. The household head's years of schooling, use of extension services, and ownership of the farm have no effect on output value, which may indicate that differences in management ability are reflected in input quantities used rather than farmer characteristics. Models (3) and (4) indicate that farms in Castanhal municipality garner higher crop revenues than those from Igarapé Açu or Bragança.

Dummy variables representing non-use of inputs indicate whether non-users have a different intercept than farmers who use all inputs in positive quantities. Models (1) and (2) indicate that farms using no family labor and farms with no upstream fallow area produce higher crop values, while Models (3) and (4) suggest that farms allocating no land to fallow earn higher revenues.

4.4 Forest product harvesting function

I now turn to forest product harvesting, an important use of fallow land beyond the ecosystem services it provides in crop production. Sixty-nine percent of farmers in the sample collect products from their fallow land. The most common products are wood and charcoal, used primarily for cooking fuel, though farmers also gather honey and forest fruits. Most of the produce is reserved for home consumption, with only one farmer selling the entire harvest. Twenty-six percent of forest product harvesters both consume and sell some of their yields. Forest products tends to be overshadowed by cropping, comprising just 14% of the income from farm activities on average, but they do make up the main source of farm income for 13% of farmers in sample. In addition, some studies argue that forest product harvesting represents an important risk mitigation or "natural insurance" strategy for small-scale farmers (Pattanayak and Sills 2001, Hedden-Dunkhorst et al. 2003). Other studies from the Amazon indicate that forest product harvesting can contribute substantially to shifting cultivators' incomes, though virgin forest may yield more lucrative products than secondary forest (Smith et al. 1999).

I estimate an equation to measure the value of fallow in harvested forest products. The dependent variable is the log of forest product value. Although most products are reserved for home consumption, I aggregate over different commodities using farmer-reported market prices in the absence of alternative weights.

The logs of on-farm and upstream fallow land are the primary regressors of interest. On-farm fallow land proxies for fallow biomass, which is the source of the harvested commodities. Upstream forest fallow may facilitate easier harvesting and more abundant products by moderating floods and soil moisture, as well as harboring insects for fruit and nut tree pollination. I again use the two alternative measures of off-farm fallow biomass derived from survey and GIS data. The equation can be represented as

$$\ln q_i = \alpha_o + \alpha_1 \ln f_i + \alpha_2 W_1 \ln F + \alpha_3 \ln H_i + \varepsilon_i$$
$$\varepsilon_i = \lambda W_2 \varepsilon + u_i$$

Here, q_i represents the value of forest product harvests. On- and off-farm fallow are again given by f_i and F, respectively, while W_1 represents the same row-normalized spatial weighting matrix as that used in the crop production function, which gives all upstream neighbors equal importance. Use of the same weighting matrix is appropriate if the externalities provided to forest products are similar to those relevant in crop production. Household characteristics expected to affect output value are included in the vector H_i. The disturbance, ε_i, is again comprised of a component that varies systematically over space with inverse distance, $\lambda W_2 \varepsilon$, and white noise, u_i. I also use Battese's (1997) approach, discussed in the crop production section, adding dummy variables to indicate observations with no fallow on their own farms and no fallow upstream.

I cannot estimate a structural production function due to missing input data, namely harvesting labor. To proxy for the labor available for collecting, I include the log of household size and the agricultural wage rate in H_i. I also include the black clay, charcoal-enriched, and poor soil type indicators and slope to control for land quality. I add variables indicating ownership of firewood and gas stoves, as cooking fuel is an important commodity for home consumption. I also include three indicators of household wealth—car ownership, television ownership, and electricity use—to examine whether low-income households are more likely to collect forest products. Other control variables include forest product prices,[24] the household head's education level and ownership of the farm, and municipality dummies.

4.4.1 Treatment of censoring in forest product harvests

Because only 69% of farms harvest forest products, the econometric model must account for censoring to consistently estimate the parameters of interest. The widely-used Tobit model incorporates features of probit and continuous regressions to account for the binary choice of whether to engage in the activity and the level of output conditional on choosing to participate. However, the Tobit restricts the effects of the explanatory variables to be equal across the binary decision and the conditional outcome. Two-part hurdle models relax this assumption, allowing for different effects across the

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[24] In the absence of data on market prices for the harvested commodities, I use village medians of farmer-reported forest product prices as regressors to avoid bias due to common measurement error and quality effects by including farmer-reported prices directly on both sides of the equation. Use of unit value cluster means outperforms other proxies for market prices in estimating price elasticities in a study using Vietnamese data (Niimi 2005). I use village medians to minimize the influence of outliers.

two equations. A hurdle model of forest product harvesting with spatially correlated error terms in both equations can be written as

$$
\begin{aligned}
&D_i = \gamma_0 + \gamma_1 \ln f_i + \gamma_2 W_1 \ln F + \gamma_3 H_i + \xi_i, \qquad D = \{0,1\} \\
&\ln q_i = \beta_0 + \beta_1 \ln f_i + \beta_2 W_1 \ln F + \beta_3 H_i + \varepsilon_i \quad if \;\; D_i = 1 \\
&\xi_i = \lambda_1 W_2 \xi + u_i \\
&\varepsilon_i = \lambda_2 W_2 \varepsilon + v_i
\end{aligned}
$$

where D denotes a dummy variable indicating participation in harvesting forest products. The selection equation is estimated using a probit model, while the conditional outcome equation can be estimated by ordinary least squares regression on the non-limit observations (discussed in Wooldridge 2001, p. 536) or truncated regression (Cragg 1971).

The Heckman selection model (1979) further generalizes the problem by allowing for correlation among the error terms of the two processes. The Heckman model is superior in theory because it corrects for selection bias, which, if present and not controlled for, can lead to inconsistent estimates of the parameters of the outcome equation. However, a drawback of the Heckman procedure is the need for an exclusion restriction—an exogenous variable that explains the binary choice but not the level of the conditional outcome. In practice, it is rare to find valid exclusion restrictions that affect one equation of the model but not the other, and economic theory often provides little guidance in this respect.

Hurdle and selection models have proven particularly useful in applications such as tobacco and alcohol consumption, where the decision to abstain may be determined by factors very different from those governing the level of consumption for those who choose to indulge. Another illustration relates to the value of fire damages: fires are less likely to occur in newer buildings, but they cause higher value damages than those in older structures when they do (Fin and Schmidt 1984).

These examples represent corner solutions or “real zeros,” rather than data censoring, similar to the case of forest product harvesting. However, factors affecting demand for forest products, such as market prices, opportunity costs of labor, and land quality, may have similar effects on both the decision to harvest and the amount produced, making a Tobit model appealing. Conversely, if the magnitudes of the effects differ across the two processes, a hurdle model is more appropriate. Because the same set of variables affects both the binary choice and conditional outcome, the lack of valid exclusion restrictions makes the Heckman selection model infeasible to implement, even though it would be ideal if reasonable exclusion restrictions were available.

I test the Tobit restriction against the two-part Cragg hurdle model, which nests the Tobit, to determine whether the coefficients vary across the two processes, again using both survey-reported fallow area and GIS canopy cover as alternative upstream fallow variables. The results of these regressions are reported in Table B7. The explanatory variables do differ in magnitude, and in some cases even sign, across the probit and non-limit regression models. Indeed, a likelihood ratio test rejects equality of the coefficients across the two equations for all four model specifications ($p = 0.00$). Therefore, I use the hurdle model estimates in the remainder of my analysis. I employ the two-part probit-least squares model rather than the Cragg approach to facilitate estimation using spatially-correlated errors and instrumental variables.

4.4.2 Identification and instrumental variables

In addition to the issues raised by censoring, potential measurement error, simultaneity, and omitted variables are again concerns in obtaining consistent parameter estimates. Similar to the omitted variable problem raised in the crop production function, poor land quality may lead farmers to allocate more land to fallow but reap lower yields of forest products, biasing the on-farm fallow coefficient downward. Measurement error may also lead to attenuation bias on the coefficients of both on- and off-farm fallow since fallow biomass is proxied by either fallow area or canopy cover. The elasticity of GIS off-farm canopy cover may also be overestimated and the elasticity of on-farm fallow area underestimated if GIS canopy cover is correlated with on-farm fallow biomass density. Simultaneity between fallow area and forest product output may bias the coefficient of on-farm fallow upwards as well, though it is less likely to affect the coefficient of off-farm fallow.

I employ similar approaches as those used in the crop production estimation to address concerns about endogeneity in the absence of panel or experimental data that would allow for cleaner identification. Control variables on land quality and farmer wealth and education are included directly in both the probit and non-limit regressions models. Spatially correlated errors are also included in both to reflect unobserved factors that vary between farms with distance.

I use instrumental variables as a final strategy to confront endogeneity issues. I employ the log of farm size as an instrument for on-farm fallow. Total farm size determines the land available for allocation to fallow. However, beyond its affect on the size of fallow land, farm area should have no direct effect on forest product harvests. Forest product prices and firewood and gas stove ownership, used as instruments for fallow in the crop production function, are not valid exclusion restrictions and are included in the forest products equation. I employ spatially-lagged values of farm size and several other household-level exogenous variables from the forest products equation as instruments for off-farm fallow.

The instruments explain much of the variation in on-farm fallow area, upstream fallow area, and canopy cover, as seen in first-stage equations with R-squared statistics of 0.74, 0.90, and 0.72, respectively (Table B8). The log of farm size is highly significant in predicting the log of fallow area (p = 0.00) across both specifications (columns 1 and 3). The spatially-lagged values of farms size and car ownership significantly predict both upstream fallow area and canopy cover, as does location in Castanhal or Igarapé Açu. Television ownership, gas stove ownership, and black clay soil on upstream farms also negatively affect upstream fallow area (column 2), while lagged firewood stove ownership and poor soil upstream help explain canopy cover (column 4).

Overidentification tests confirm that the instruments are uncorrelated with forest product harvesting decisions and output value (p = 0.40-0.89 and 0.77-0.95). They area also uncorrelated with the outcome variables individually, as shown by including each in the outcome equations (p = 0.14-0.88). Table B9 reports the results of these tests. Certain lagged household characteristics, including education, farm ownership, electricity use, and slope were not used as instruments because they were found to be correlated with the forest product harvesting decision or conditional value.

Hausman test results indicate that on- and off-farm fallow can be considered exogenous to the forest product harvesting decision in Model (1) but not in Model (3), nor are they exogenous to the value of forest products conditional on harvesting.

Therefore, the IV estimates of the probit and non-limit regressions are consistent, while the regular SEM-probit and non-limit regression estimates are not.

4.4.3 Results

Tables 4.6 and 4.7 show the results of the forest product harvesting participation and outcome equations, respectively. Columns (1) and (2) of Table 4.6 report probit and IV probit coefficient estimates using survey-derived off-farm fallow area as the off-farm fallow variable. Columns (3) and (4) instead use GIS canopy cover. Table 4.7 follows the same pattern, with columns (1) and (2) giving non-limit regression and IV estimates using survey-reported off-farm fallow area, and columns (3) and (4) using GIS canopy cover. The spatial correlation coefficient of the probit equation error term is positive and significant across all four models, indicating that unobservable factors do have similar effects on neighbors' harvesting decisions. The error terms are not significantly spatially correlated in the non-limit regressions, however.

Table 4.6 Forest product harvesting: participation equation

	SEM [25] Probit (1)	SEM-IV probit (2)	SEM Probit (3)	SEM-IV probit (4)
Log on-farm fallow area	0.281***	0.370***	0.300***	0.362***
	[0.110]	[0.146]	[0.094]	[0.159]
Log off-farm fallow – upstream survey fallow area	0.430	0.425		
	[0.278]	[0.302]		
Log off-farm fallow – 3 km upstream GIS canopy cover			1.268	3.390**
			[0.809]	[1.581]
Forest product price (village median)	-0.224790	-0.181	0.099	0.069
	0.182062	[0.168]	[0.108]	[0.119]
Log household size	0.965***	0.962***	0.854***	0.890***
	[0.300]	[0.260]	[0.234]	[0.246]
Agricultural wage rate	-0.245***	-0.234***	-0.201**	-0.219***
	[0.010]	[0.095]	[0.081]	[0.086]
Household head schooling years	0.051	0.061*	0.042	-0.043
	[0.047]	[0.043]	[0.038]	[0.260]
Farm owner (binary)	0.303	0.274	0.003	0.046
	[0.294]	[0.275]	[0.249]	[0.045]
Own car (binary)	-0.975***	-0.936***	-0.849**	-0.847**
	[0.403]	[0.397]	[0.388]	[0.390]
Own television (binary)	0.047	-0.015	0.034	0.168
	[0.314]	[0.320]	[0.292]	[0.302]
Use electricity (binary)	-0.841***	-0.744***	-0.773***	-0.753***
	[0.335]	[0.316]	[0.289]	[0.296]
Own firewood stove (binary)	0.293	0.326	0.358	0.309
	[0.329]	[0.319]	[0.290]	[0.311]
Own gas stove (binary)	-1.498***	-1.478***	-1.089***	-1.215***
	[0.552]	[0.553]	[0.404]	[0.476]
Black clay soil (binary)	0.851*	0.858*	0.595*	0.591*
	[0.534]	[0.550]	[0.470]	[0.430]
Charcoal-enriched soil (binary)	0.197	0.185	0.052	0.0422
	[0.396]	[0.394]	[0.365]	[0.386]
Poor soil (binary)	-0.381	-0.311	-0.279	-0.170
	[0.602]	[0.609]	[0.525]	[0.504]
Slope	-0.008	-0.020	-0.024	-0.065*
	[0.054]	[0.053]	[0.045]	[0.051]
Castanhal municipality (binary)	0.742**	0.685**	0.813**	1.435***
	[0.404]	[0.423]	[0.431]	[0.632]
Igarapé Açu municipality (binary)	1.497***	1.401***	0.887***	1.092***
	[0.479]	[0.509]	[0.414]	[0.456]
No on-farm fallow area (binary)	0.248	0.581	0.047	0.428
	[0.483]	[0.592]	[0.425]	[0.577]
No upstream fallow area (binary)	-2.858**	-3.018**		

---

[25] Spatial errors probit model estimated using Gibbs sampler algorithm in Matlab (LeSage 1998).

	[1.441]	[1.384]		
Constant	0.936	0.364	-3.971*	-11.186***
	[1.568]	[1.667]	[2.783]	[5.007]
Spatial error correlation coefficient (λ)	0.535*** [0.245]	0.545*** [0.234]	0.490*** [0.252]	0.506*** [0.237]
Observations	236	236	261	261
McFadden R-squared	0.30	0.29	0.25	0.26

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Table 4.7 Forest product harvesting: conditional outcome equation

	SEM (1)	SEM-IV (2)	SEM (3)	SEM-IV (4)
Log on-farm fallow area	0.065	0.283**	0.021	0.264
	[0.107]	[0.139]	[0.113]	[0.166]
Log off-farm fallow – upstream survey fallow area	0.549** [0.278]	0.548* [0.322]		
Log off-farm fallow – 3 km upstream GIS canopy cover			0.913 [0.811]	0.093 [1.418]
Forest product price (village median)	0.037 [0.187]	0.116 [0.191]	0.150 [0.176]	0.202 [0.179]
Log household size	0.087	0.113	0.225	0.234
	[0.265]	[0.264]	[0.261]	[0.259]
Agricultural wage rate	0.027	0.01	-0.028	-0.032
	[0.100]	[0.098]	[0.088]	[0.089]
Household head schooling years	0.03	0.041	0.071	0.082*
	[0.047]	[0.047]	[0.046]	[0.046]
Farm owner (binary)	-0.191	-0.201	-0.325	-0.267
	[0.267]	[0.264]	[0.271]	[0.270]
Own car (binary)	1.215**	1.217**	1.102**	1.110**
	[0.525]	[0.517]	[0.512]	[0.509]
Own television (binary)	0.631**	0.652**	0.691**	0.668**
	[0.274]	[0.271]	[0.273]	[0.278]
Use electricity (binary)	-1.078***	-1.102***	-1.031***	-1.087***
	[0.270]	[0.268]	[0.269]	[0.273]
Own firewood stove (binary)	0.406	0.386	0.311	0.406
	[0.378]	[0.373]	[0.392]	[0.391]
Own gas stove (binary)	-0.017	-0.088	0.104	0.027
	[0.308]	[0.305]	[0.305]	[0.308]
Black clay soil (binary)	0.963**	0.968**	0.758*	0.786*
	[0.413]	[0.408]	[0.403]	[0.402]
Charcoal-enriched soil (binary)	-0.124	-0.079	-0.439	-0.359
	[0.386]	[0.382]	[0.394]	[0.397]
Poor soil (binary)	0.44	0.522	0.612	0.59
	[0.537]	[0.534]	[0.522]	[0.530]
Slope	-0.064	-0.084*	-0.073	-0.076

	[0.048]	[0.049]	[0.047]	[0.052]
Castanhal municipality (binary)	0.647	0.625	0.656	0.434
	[0.442]	[0.446]	[0.484]	[0.578]
Igarapé Açu municipality (binary)	0.235	0.136	-0.068	-0.221
	[0.462]	[0.481]	[0.409]	[0.427]
No on-farm fallow area (binary)	-0.178	0.352	-0.113	0.562
	[0.563]	[0.604]	[0.560]	[0.616]
No upstream fallow area (binary)	0.401	0.007		
	[1.633]	[1.655]		
Constant	2.942	2.116	0.953	3.062
	[1.908]	[2.003]	[3.276]	[5.100]
Spatial error correlation coefficient (λ)	0.153	0.176	0.084	0.090
	[0.186]	[0.197]	[.214]	[0.182]
Observations	167	167	184	184
R-squared	0.19	0.20	0.17	0.18
Log likelihood	-293.23	-291.62	-331.08	-330.16

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

While I use separate probit and non-limit regression models to estimate the parameters of the hurdle model, the combined effect or unconditional elasticity of the fallow variables are the main parameters of interest from the model of forest product harvesting. The unconditional elasticity is the percent change in the value of forest products stemming from a 1% change in fallow, accounting for the effects on the probability of harvesting and on the value of the harvest conditional on participating. McDonald and Moffit (1980) derive the decomposition of these two effects in the Tobit context, showing that

$$E(y \mid x) = \Pr(y > 0 \mid x) \cdot E(y \mid y > 0, x)$$

Log differentiating this expression reveals that the unconditional elasticity is simply the sum of the probability elasticity and the conditional elasticity. The non-limit regression equations estimate the conditional elasticity directly, since product value and fallow are expressed in log form. I calculate the probability elasticities using the coefficients from the probit models, which can be expressed as

$$\frac{d \ln \Pr(q > 0)}{d \ln f} = \gamma_1 \frac{\varphi(\gamma z)}{\Phi(\gamma z)}$$

where γ_1 is the coefficient of the log of on-farm fallow from the probit equation, and γz is the linear prediction.

Table 4.8 reports the probability, conditional, and unconditional elasticities of on- and off-farm fallow in forest product harvesting. The unconditional output elasticity of on-farm fallow is positive across all four models, varying from 0.17 to 0.49. However, it is higher in magnitude and significantly different from zero only in Models (2) and (4), when the IV approach addresses the endogeneity of on- and off-farm fallow. This finding suggests that omitted variables and measurement error may indeed bias the estimates of the probability and conditional elasticities downward. These results confirm that on-farm fallow makes an important contribution to the value of forest products, as expected. In fact, the elasticities derived from the IV estimates suggest that on-farm fallow contributes close to 50% of the value of forest products.

Table 4.8 Forest product harvesting elasticities

		(1)	(2)	(3)	(4)
Log on-farm fallow area	Probability elasticity	0.14**	0.19***	0.15***	0.22**
		(0.06)	(0.07)	(0.05)	(0.10)
	Conditional elasticity	0.06	0.28**	0.02	0.26
		(0.11)	(0.14)	(0.11)	(0.17)
	Unconditional elasticity	0.21	0.47***	0.17	0.49**
		(0.13)	(0.17)	(0.13)	(0.21)
Log upstream fallow – survey fallow area	Probability elasticity	0.22	0.22		
		(0.14)	(0.16)		
	Conditional elasticity	0.55*	0.55*		
		(0.28)	(0.32)		
	Unconditional elasticity	0.77**	0.76*		
		(0.34)	(0.38)		
Log upstream off-farm fallow – GIS canopy cover (3 km radius)	Probability elasticity			0.62	2.10***
				(0.40)	(0.81)
	Conditional elasticity			0.91	0.09
				(0.81)	(1.41)
	Unconditional elasticity			1.53	2.19
				(0.95)	(1.74)

Standard errors of the probability elasticities were calculated using the delta method.
* significant at 10%; ** significant at 5%; *** significant at 1%

The estimates of the unconditional elasticity of off-farm fallow are also all positive, spanning 0.62-2.19. Similar to the results from the crop production function, the elasticity of upstream fallow area is significantly greater than zero (Models 1 and 2). The elasticity of upstream canopy cover is extremely high in Model 3, though not significantly different from zero, which may result from the bias caused by collinearity with on-farm biomass density. The IV estimate (Model 4) is again not significantly different from zero, but the magnitude of the elasticity is closer to that of the upstream fallow area variable. These results suggest that farms located downstream of neighbors with higher levels of forest fallow garner higher incomes from forest products, even accounting for positive spatial correlation in omitted variables affecting neighbors' harvesting decisions. The net effect is positive and statistically significant for two out of four estimates. Thus, these findings provide some support the hypothesis that upstream forest fallow provides positive externalities not only in crop production but also in forest product harvests, thought the results are less conclusive than those from the crop production function.

4.4.4 Resampling and robustness analysis

I carry out similar tests of robustness to those used in the crop production section to investigate whether the results hold across different sub-groups of farmers. Excluding farms from the top and bottom tenth percentiles of on-farm fallow from the probit and non-limit regressions, I find that the results are largely stable. On-farm fallow has a positive and significant effect on the probability of harvesting across the different sub-samples, though it has no significant effect on the conditional value of the harvest (Tables B10-B13). The effect of upstream fallow area is somewhat less robust across different groups—farms with more fallow upstream experience a much larger impact on the probability of harvesting, but find less of an effect on the conditional harvest value. Upstream canopy cover has a consistent effect on the probability of harvesting across different sub-samples, but farms with less upstream canopy cover reap greater benefits in terms of harvest value.

Figures B5-B8 plot estimates of the total elasticities of on-farm and upstream fallow with 95% confidence intervals from probit and non-limit regressions using the leave-one-out cross-validation procedure. The total elasticity estimates do vary quite a bit, ranging from 0.09-0.20 for on-farm fallow, 0.52-0.78 for upstream fallow area, and 1.05-1.52 for upstream canopy cover, with means of 0.130-0.155, 0.701, and 1.369, respectively. Thus, while total elasticity estimates for forest product harvests with respect to on-farm and upstream fallow are positive across different sub-samples of farmers, they are more variable than those from the crop production function.

I also investigate whether fallow externalities only arise from upstream forest cover by estimating the probit and non-limit regressions including downstream fallow. I find that downstream fallow has no significant effect on the probability of harvesting forest products, and the coefficient is actually negative across all four models (Table B14). The results from the conditional outcome equation are less conclusive—Models (2)-(4) show downstream fallow to have a positive effect on harvest value, though it is only significant in Model (4). Thus, I cannot confirm whether the positive effects of off-farm fallow on forest product harvests are strictly hydrological, flowing from upstream to downstream, or whether pollination, tree seed availability, or other potential forest ecosystem services may play a role.

4.4.5 Other factors affecting forest product harvests

Turning to the other explanatory variables in the hurdle model of forest product harvesting, labor availability is important in the decision to collect forest products, as indicated by the positive and significant coefficient of the log of household size and the negative and significant coefficient of the wage rate in the probit equation. Ownership of a gas stove is negatively associated with harvesting forest products, as expected given these farms' decreased reliance on firewood as a cooking fuel. Farms that do not own a car or use electricity are more likely to collect forest products, implying that low-income farmers rely more heavily on forest products than do better-off households. However, car and television ownership have the opposite effect on the conditional value of forest products, suggesting that wealthier households reap greater value from this activity when they choose to participate. The effect of electricity use is again negative, though. Families with a more educated household head also earn higher revenues from harvesting. Land quality affects harvests as well: favorable black clay soils and less steeply-sloped land increase the conditional value of harvested products. Farmers located in Castanhal and Igarapé Açu are more likely to collect forest products than those in Bragança. In addition, households' whose upstream neighbors maintain no fallow area are significantly less likely to harvest any forest products Village median forest product prices, firewood stove ownership, and farm ownership do not have significant effects on the probability of harvesting or on conditional harvest value.

4.5 Total on- and off-farm fallow elasticities

To better understand the economic significance of forest fallow services in farm activities, I calculate the total farm output elasticity of on- and off-farm fallow using the results from all four models of the crop and forest product equations. The total output elasticities of on- and off-farm fallow account for their contribution to both crop and forest product income and vary by farm with the share of income from each activity. Each column corresponds to the set of elasticity estimates used from the crop output and forest product value equations to calculate the total output elasticities (Table 4.9). For example, column (1) reports the results using the SEM estimates of the crop output elasticities (Table 4.5, column 1) and the SEM-probit and non-limit regression estimates of the forest product elasticities (Tables 4.6-4.7, column 1) of on-farm fallow and upstream fallow area.

The mean elasticity of on-farm fallow ranges from 0.10-0.22 depending on the estimates used, but is significantly different from zero in all four specifications. This consistently positive mean elasticity underscores the importance of forest fallow to farms in the Zona Bragantina in providing both consumable products and ecological support services.

Table 4.9 Total output elasticities of on- and off-farm fallow

	(1)	(2)	(3)	(4)
Total output elasticity of on-farm fallow (sample mean)	0.11* (0.06)	0.17** (0.08)	0.10* (0.06)	0.22** (0.10)
Total output elasticity of upstream fallow (sample mean)	0.42** (0.16)	0.43** (0.19)	1.03** (0.49)	0.66 (0.81)

Note: sample means of standard errors given in parentheses were calculated using the estimated standard errors from the previous analyses.

In addition, the mean output elasticity of upstream fallow is significantly different from zero in three of the four sets of estimates, spanning 0.42-1.03. The effect of off-farm fallow on farm revenue appears to be important both statistically and in magnitude. Moreover, at least for crop production, the externalities appear to be hydrologically-based, as indicated by the positive and significant effect of upstream but not downstream forest cover on crop value.

These findings support the hypothesis that upstream forest fallow provides flows of economically significant ecological services to farms in the Zona Bragantina. This evidence suggests that off-site hydrological regulation may be important even in low and moderately sloped regions with porous soils, not only in steeply-sloped, clayey areas like Ruteng National Park, Indonesia, where forest hydrological externalities also significantly contribute to farm productivity (Pattanayak and Kramer 2001, Pattanayak and Butry 2005). These hydrological support services may justify continued allocation of significant amounts of land to forest fallow in the future, even if farms increasingly substitute chemical fertilizer for fallow-based soil nutrients.

It is unclear from this analysis whether farms recognize these off-site ecological services and respond to them in their own land allocation decisions. I also cannot infer from these results whether farmers allocate land between cultivation and fallow efficiently, either from a private or social perspective. I turn to these two questions in the chapters that follow.

5 Strategic fallow management: a spatial analysis

Results from the crop and forest product equations imply that off-farm fallow may provide significant ecological services to farms in the Eastern Amazon. If off-farm fallow does provides ecological services that fulfill some of the same functions as on-farm fallow, it is unclear whether farmers recognize these benefits or take advantage of them through their own allocation of land. In this section, I estimate an equation to determine the impact of upstream forest fallow on downstream farms' land allocation.

The theoretical model of shifting cultivation discussed in Chapter 3 predicts that neighboring forest fallow has an ambiguous effect on own-farm land allocation, depending on the relative strengths of the externalities provided to crops and forest products. If the externality is more important in cropping than forest products, then farms will tend to expand cultivation and contract the area under fallow in response to an increase in upstream forest cover; if the forest product externality dominates, the reverse is true. Since cropping is the dominant activity in the Zona Bragantina, I might expect farmers to reduce their own fallow land and expand cultivated area to take advantage of their neighbors' fallow biomass. Such strategic behavior would lead to negative spatial correlation in fallow. Nelson and Hellerstein (1997) find a negative spatial lag in forest cover in central Mexico, though the authors posit no explanation for this relationship.

5.1 Econometric model

Identifying spatial correlation in an observed dependent variable is complicated by the potential for underlying spatial correlation in unobserved factors affecting land use, so I allow for spatial correlation in both processes. I use a general spatial model that incorporates both a spatial lag in the dependent variable and spatial autocorrelation in the error term, which can be written as

$$\frac{f_i}{L_i} = \lambda_o + \lambda_1 Z_i + \rho W_1 F + \varepsilon_i$$
$$\varepsilon_i = \lambda W_2 \varepsilon + u_i$$

The dependent variable is the percent area under fallow. As in the previously estimated equations, f_i represents on-farm fallow area, while F is a vector of all other farms' fallow area, and L_i is total available land. I do not take logarithms of the fallow variables in this analysis to avoid problems raised by the 14% of observations that allocate no land to fallow. The row-normalized spatial weighting matrix W_1 serves to indicate which farms are upstream neighbors of farm i and gives each upstream neighbor equal weight. Thus, I estimate the percent of on-farm fallow area as a function of the weighted average of upstream fallow area, $W_1 \ln F$.

Z_i is a vector of household attributes expected to affect land allocation, while ε_i is a disturbance term that may itself be spatially correlated. W_2 is spatial weighting matrix of inverse distances applied to the disturbance, while u_i is a white noise error term. As in the crop and forest product equations, the different structures for the two spatial weighting matrices both ensures identification of the spatial autoregressive parameters and reflects the different likely patterns of spatial variation in the forest externality and the unobserved variables affecting land use. I interpret a test of the significance of ρ, the spatial lag coefficient, as a test for strategic behavior in land use.

Estimation of the spatial lag model must address the endogeneity caused by dependence among observations of the fallow variable to ensure consistent parameter estimates. The asymmetric direction of the externality (upstream to downstream) decreases the likelihood that the spatial lag of fallow will be correlated with the residual of the percent fallow equation. However, I employ an IV approach to control for potential simultaneity between on- and off-farm fallow.

The instrumental variables estimator provides asymptotically consistent parameter estimates of the spatial lag model, though it is less widely used than maximum likelihood (Anselin 1988). Anselin suggests using spatial lags of the exogenous regressors in the model as a possible set of instruments for the lagged dependent variable. I follow this approach. Thus, the weighted average of prices, household attributes, and agroecological characteristics faced by each farm's upstream neighbors are used to predict off-farm fallow to address simultaneity issues. Table C1 reports the first stage equations for off-farm forest fallow.

I include several household characteristics in the fallow equation expected to affect land allocation decisions. Forest product prices and firewood- and gas-stove ownership affect returns to fallowing from forest product harvesting. Likewise, output prices of annual and perennial crops and fertilizer prices affect the opportunity cost of land allocated between fallow and cultivation. The theoretical model in Chapter 3 predicts that higher forest product and fertilizer prices increase land allocated to fallow, while higher crop output prices favor moving land into cultivation. I include transportation costs and frequency in case market access affects land allocation decisions. The log of household size and the wage rate affect labor availability for land clearing and cultivation, though the theoretical model does not unambiguously predict the direction of the effect. Total farm size determines land availability for allocation to fallow, and other studies of shifting cultivation find smaller farms to cultivate land more intensively (Smith et al. 1999, Coomes et al. 2000). I include several proxies for household wealth, including farm ownership, car and television ownership, and electricity use. Agroecological characteristics may also be important if farms with more steeply sloped land or poorer quality soils allocate more land to fallow to prevent erosion or nutrient loss. I include the household head's schooling years and municipality dummies as additional controls.

5.2 Results

Table 5.1 presents the results from the spatial lag model of fallow area. I report estimates using the survey-reported upstream fallow and GIS upstream canopy cover variables in columns 1 and 2, respectively. Rho represents the coefficient on the weighted average of neighbors' fallow land. Results from both models indicate that neighbors' fallow area is not a significant determinant of percent area under fallow[26]. In fact, the coefficient is actually positive across both specifications, rather than negative, as would be expected if farms substitute neighbors' forest fallow services for their own in crop production. In addition, λ is not significantly different from zero and is negative in both models, suggesting that unobserved factors varying with distance between farms do not explain a substantial portion of the variation in the percent of farmland allocated to fallow.

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[26] Results are not qualitatively different if total area or percent area under fallow are used as either the dependent variable or the spatially-lagged variable.

Table 5.1 Spatial lag model of percent on-farm fallow area (2SLS estimates)

	(1)	(2)
Spatial lag coefficient) – upstream survey fallow area (ρ)	0.001	
	[0.002]	
Spatial lag coefficient – 3 km upstream GIS canopy cover (ρ)		0.009
		[0.007]
Forest product price (farmer-reported)	0.003**	0.002*
	[0.001]	[0.001]
Annual crop price index	-0.106	-0.092
	[0.121]	[0.102]
Perennial crop price index	-0.023	-0.007
	[0.016]	[0.016]
Fertilizer price index	0.211	0.221
	[0.314]	[0.299]
Transportation cost	-0.542	-3.711
	[5.062]	[5.293]
Transportation frequency	-0.02	-0.027
	[0.018]	[0.017]
Wage rate	-0.009	-0.001
	[0.015]	[0.013]
Log household size	-0.004	0.013
	[0.040]	[0.038]
Log farm size	0.077***	0.074***
	[0.017]	[0.018]
Farm owner (binary)	0.132***	0.131***
	[0.042]	[0.040]
Log household head years of schooling	0.008	0.007
	[0.007]	[0.007]
Own firewood stove (binary)	0.06	0.041
	[0.054]	[0.054]
Own gas stove (binary)	-0.074	-0.066
	[0.056]	[0.054]
Own car (binary)	-0.05	-0.054
	[0.072]	[0.069]
Own television (binary)	0.051	0.033
	[0.048]	[0.046]
Use electricity (binary)	-0.110**	-0.073
	[0.049]	[0.048]
Black clay soil (binary)	-0.025	-0.052
	[0.070]	[0.068]
Charcoal-enriched soil (binary)	0.04	0.057
	[0.063]	[0.064]
Poor soil (binary)	0.06	0.12
	[0.090]	[0.081]
Slope	0.004	0.005
	[0.009]	[0.008]

Castanhal municipality (binary)	0.155*	0.152*
	[0.090]	[0.087]
Igarapé Açu municipality (binary)	0.028	0.024
	[0.096]	[0.091]
Constant	0.219	-0.103
	[0.396]	[0.406]
Spatial error correlation coefficient (λ)	-0.067	-0.058
	[0.191]	[0.197]
Observations	236	261
R-squared	0.23	0.26
Log likelihood	-29.56	-31.98

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Factors that do affect farms' distribution of land between fallow and cultivation include prices, farm size, and farm ownership. Crop prices, both annual and perennial, have a negative effect on fallow, while fertilizer and forest product prices has a positive effect, though only the latter coefficient is significantly different from zero. These results confirm the predictions of the theoretical model in Chapter 3 that crop prices raise the opportunity cost of fallowing, while fertilizer and forest product prices increase the opportunity cost of cultivation. Electricity use is negatively associated with more on-farm fallow in Model 1, indicating that poorer households or those with less access to infrastructure cultivate land less intensively. Fallowing increases with steeper slopes and poor soils and decreases with black clay soils, though these effects are not statistically significant. As anticipated, ownership of a firewood stove has a positive effect on fallow area, and ownership of a gas stove has a negative effect, though again not at statistically significant levels. Household size, wage rate, transportation cost and frequency, car and television ownership, and education of the household head also have no effect on fallow allocation. These factors aside, farms in Castanhal allocate more land to fallow compared to those in Igarapé Açu or Bragança.

The outcome of the spatial model of fallowing suggests that farms do not respond strategically to their neighbors' fallow land when determining their own land allocation. However, the strength of this conclusion is tempered by the ambiguous prediction from the theoretical model, which suggests that a farm's response to upstream fallow depends on whether it garners more important externalities in crop production or forest product harvesting. Since the econometric results from Chapter 4 indicate that off-farm fallow provides ecological services to both activities, the two effects may cancel each other out in aggregate, leading upstream fallow to have little impact on farmers' land use decisions even if they recognize the ecological services and wish to take advantage of them.

6 Are farmers allocating land between cultivation and fallow optimally?

As seen in the crop, forest product, and total output elasticity results discussed in Chapter 4, on-farm fallow is positively associated with farm output and it may also provide positive externalities to downstream neighbors. However, the total output elasticity does not capture the net benefits of on-farm fallow land, which must take into account the opportunity cost of land left out of cultivation. Indeed, another study from Pará calculates that converting fallow to cultivated land and replacing the lost biomass nutrients entirely with purchased chemical fertilizer would lead to higher farm profits (Toniolo and Uhl 1995). Likewise, a study from the Philippines finds that use of hedgerows improves soil quality, but the net improvement in farm profits is minor due to the loss of labor and land used directly in cultivation (Pattanayak and Mercer 1998).

I estimate the crop output elasticity of cultivated land to be considerably higher than the total output elasticity of on-farm fallow (0.41-0.44 compared to 0.10-0.17, respectively). Given the direct tradeoff between land used for cultivation and fallow, there may be gains to farmers from reallocating land between fallow and cropping, particularly since over 50% of land area is left out of cultivation at any one time among surveyed farms.

Any such gains would be individual to the farm and may come at a cost to downstream farmers who benefit from forest hydrological services upstream. However, it may be of interest to identify whether a private land tenure system such as prevails in the Zona Bragantina at least fosters efficient land allocation from an individual perspective.

Similar to López (1997), I construct a measure of the optimality of land allocation between cultivation and fallow, which I term the net elasticity of cultivated land. The net elasticity of cultivated land represents the percent change in farm income from a 1% expansion of cultivated area into fallow area. It also accounts for the cost of labor used for clearing land, which increases with cultivated area and with fallow biomass[27]. This term simply subtracts the marginal costs of cultivated area—namely, the marginal value of the lost fallow land and labor clearing costs—from the marginal benefits of increased crop production. The equation corresponds to the first order condition for efficient land allocation given in equation (17) from case 3 of Chapter 3, substituting in for the steady state values of μ and η[28]. Written in elasticity form, the term is given by

$$\varepsilon_{net} = \frac{r_{crop}}{\pi_{tot}}\left(\varepsilon_x - \frac{x}{r_{crop}} l\right) - \left(\frac{r_{crop}}{\pi_{tot}}\left(\frac{x}{f}\varepsilon_f\right) + \frac{r_{for}}{\pi_{tot}}\left(\frac{x}{f}\xi_f\right)\right)\left(\frac{1+r}{r + x/(x+f)}\right)$$

The net elasticity of cultivated land (ε_{net}) varies with the amount of land under fallow (f) and cultivation (x), the relative contributions of cropping and forest products to income (r_{crop}, r_{for}), total farm profits (π_{tot}), and marginal land-clearing costs (l), factors that vary across all farms in the sample. It also depends on the elasticities of crop production with respect to cultivated (ε_x) and fallow area (ε_f) and on the elasticity of forest product harvests with respect to fallow area (ξ_f), which can be approximated by the estimated parameters from the crop and forest product equations discussed in Chapter 5.

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[27] Manual slash-and-burn is more common in the region than renting expensive mechanized equipment, and farmers in the Zona Bragantina spend 30 labor days per year clearing land for cropping on average. Each additional hectare of land under production requires approximately 3 days of labor at a cost of $B 25 (US$1 = $B 3). I derive marginal land clearing labor, which I value at the agricultural wage rate, by regressing land clearing labor on cultivated and fallow land (with a quadratic term for land). The Appendix presents the results of this regression (Table D1).

[28] To calculate whether each farm's land allocation is socially rather than privately optimal, this term should account for any contribution of fallow to downstream neighbors' output, corresponding to the first order condition for land allocation from case 1of Chapter 3 (equation (2)).

Finally, the rate of interest (r) is an important determinant of the optimal allocation of land between cultivation and fallow. Higher interest rates justify lower levels of fallow biomass since the value of fallow is discounted more heavily (López 1997). In the absence of primary data on interest rates in the region, I allow the interest rate to take on different values representing a range of plausible conditions in the Zona Bragantina[29].

Optimal allocation of land between cultivation and fallow implies that the net elasticity of land is equal to zero. If the net elasticity of land is significantly greater than zero at the 1% level[30], I consider the farm to be over-fallowing; if it is significantly less than zero, the farm is under-fallowing.

As an additional caveat, it is worth noting that the condition for optimal land allocation assumes that farmers are risk neutral, or alternately that fallow and cultivated land do not have different effects on the variance of crop output. However, if farmers are risk averse and fallowing is a risk-mitigating input, then optimal land management may entail a greater allocation of land to fallow but appear as over-fallowing.

Assuming a conservatively low 10% interest rate and calculating the net elasticity of land for every farm that allocates some land to fallow, I find that most farmers are fallowing optimally from an individual perspective (Table 6.1). The average farm with some fallow land would not significantly increase farm profits by reallocating land between fallow and cultivation according to three out of the four models. I cannot reject optimal land allocation for 51-76% of all farms in the sample. Only 3-6% of farms

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[29] I consider interest rates of 6%, 10%, and 20% to reflect the range in subsidized credit programs and market interest rates faced by farmers in the region. The Fundo Constitucional de Financiamento do Norte (FNO) credit program offers subsidized credit of up to $B5000 to farmers at 6% interest (Borner 2005). Meanwhile, market interest rates available to farmers in Brazil tend to fall within 16-20% (ERS/USDA 2005).

[30] Of course, if a less conservative significance level is used for hypothesis testing, such as 10%, the number of farms that appear to manage land optimally decreases quite substantially.

under-allocate land to fallow. Meanwhile, the remaining 18-46% do devote excessive amount of land to fallow, a non-negligible proportion of farmers. Figures D1-D4 present histograms of the net elasticity of cultivated land measures to give a more complete picture of the distribution of over- and under-fallowing across farmers. They also indicate that most farms cluster at zero, though there are more farms devoting too much land to fallow than there are farms allocating too little. While the elasticity estimates varies based on the econometric models used and entail a degree of imprecision, the extent of over-fallowing is underscored by the fact that at least 18% of farms with some fallow land could significantly increase profits by reallocating fallow land to cultivation according to all specifications.

Table 6.1 Fallow management indicators assuming 10% interest rate

	(1)	(2)	(3)	(4)	Observations
Net elasticity of cultivated land[31]	0.07	-0.04	0.14*	-0.07	233
	(0.28)	(0.34)	(0.27)	(0.35)	
Over-fallow (1 = yes, 0 = no)	0.36	0.18	0.46	0.21	269
Under-fallow (1 = yes, 0 = no)	0.04	0.06	0.03	0.05	269
Optimal fallow (1 = yes, 0 = no)	0.60	0.76	0.51	0.74	269

* significant at 10%; ** significant at 5%; *** significant at 1%

I report the same fallow management indicators assuming 6% and 20% interest rates in Tables D2 and D3. Unsurprisingly, the appearance of over-fallowing increases if farms face a 20% interest rate. In this case, the average farm is more likely to experience a significant increase in profits from shifting land out of fallow into cultivation according to both Models (1) and (3). If farmers can obtain credit at much lower interest rates, such as those offered by the FNO, most seem to be fallowing efficiently. However, this situation is quite unlikely given that the FNO rations these loans to $B5000 per farmer, and in practice, many find the loans inaccessible (Borner 2005, Andrae and Pingel 2001).

These results contrast those of López (1993, 1997, 1998), who finds farmers in Ghana and Cote d'Ivoire holding fallow in common property to clear excessive amounts of fallow for cultivation relative to the social optimum, indicating that private property ownership may improve the efficiency of land management. However, without incorporating the value of fallow externalities into the net elasticity of land, these findings are not directly comparable with those from the West Africa studies. In addition, it is unclear from these results whether over-fallowing can be explained by market failures such as credit constraints, or transportation costs, risk aversion, or other potential barriers to intensification, an issue I explore in the next section.

6.1 Why are farmers over-fallowing?

I examine the determinants of the net elasticity of cultivated land, a measure of the extent of over-fallowing from the farm's individual perspective, to investigate potential constraints to efficient land use. Market imperfections can affect fallow management by limiting the use of purchased inputs and capital investments important for continuous cultivation and restricting the amount of land that can be profitably cultivated at any one time. Building on the literature on the causes of tropical deforestation, I consider a variety of economic and agroecological variables that may drive land-use decisions.

Much of the literature on deforestation uses a land-rent model as a conceptual basis, noting that the net benefits to different land uses vary with agroclimatic and socioeconomic characteristics at the local or household level. These studies have drawn attention to factors such as rainfall, road access, and population density, among others, as

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[31] The net elasticity of cultivated land is only defined for farms with some amount of fallow land.

important determinants of land conversion. Research focusing specifically on land allocation to forest fallow in the Amazon raises similar issues, highlighting off-farm income, distance from markets, soil quality, and land and labor availability (Scatena et al. 1996, Coomes et al. 2000, Perz and Walker 2002). These studies have not explicitly considered whether land use is efficient from the individual or social perspective, though they offer intuition about the expected effects of a range of variables.

Liquidity constraints may be one factor leading to suboptimal input allocation (López and Romano 2000). The theoretical model in Chapter 3 predicts that liquidity constraints restrict input purchases and spur farmers to allocate land away from cultivation to fallow. Farms may be constrained in the amount of land they can profitably cultivate if they lack sufficient savings, cash income from off-farm sources, or credit to purchase optimal quantities of inputs. However, recent studies from tropical forested regions reach no firm conclusions about the role of credit in forest and fallow management. Municipio-level credit infrastructure does not significantly affect deforestation levels when controlling for population and road density (Pfaff 1999). While commercial credit use among households in a Pará frontier community had no impact on the share of land under fallow, off-farm income and ownership of mechanized equipment were negatively associated with fallowing, suggesting that liquidity may indeed affect fallow management (Perz and Walker 2002). Municipio-level use of subsidized credit use is positively associated with deforestation in Chiapas and Oaxaca, Mexico (Deininger and Minten 2002). A bio-economic simulation model of the Zona Bragantina indicates that improved credit access at subsidized interest rates does not affect land use or technology choice. However, the model does not adequately reflect the fixed capital-intensive costs of establishing perennial production, and increased credit may enable farmers to increase land under continuous cultivation under real-world circumstances (Borner 2005).

Small-scale farmers in the Brazilian Amazon can access commercial credit through programs funded by the FNO. However, despite the FNO's mandate to target peasants with its agricultural credit schemes, complicated bureaucracy and other transaction costs render loans inaccessible to many poor farmers (Andrae and Pingel 2001). Only 31% of sampled farmers in the Zona Bragantina obtained any credit from a bank or cooperative during the previous decade (Table 4.1).

I use farmer-reported commercial credit use and off-farm income (separated into wage income from agricultural and non-agricultural activities and non-wage income such as pensions, scholarships, and remittances) as three binary measures of liquidity. Actual credit use may be arguably endogenous, depending not only on access to credit but also risk preferences, shocks, and farm technology choice. In addition, credit access itself could be vulnerable to reverse causality with land and input management if farmers parlay better farm management abilities into improved credit-worthiness. However, including this variable serves as an indicator of the correlation between credit availability and land and input management even if I cannot draw firm conclusions about the direction of causality. This analysis also offers a complementary perspective to studies examining municipio-level credit availability by examining household credit use. Off-farm income may also be endogenous if better management skills lead to improved off-farm employment opportunities, again preventing strong conclusions about the direction of causality, but still demonstrating whether indicators of liquidity are correlated with fallow and input use.

While evidence on the role of credit and land use remains ambiguous, the effect of transportation infrastructure on forest cover is quite consistent across many studies. Road density and distance to regional and national capitals significantly predict deforestation in the Amazon (Pfaff 1999, Chomitz and Thomas 2003). The road infrastructure-deforestation relationship also holds in other tropical forested regions, including Belize, Mexico, and Thailand (Chomitz and Gray 1996, Nelson and Hellerstein 1997, Cropper, Puri, and Griffiths 2001). I include village-level transportation frequency and household-level distance to the local market to reflect the effect of transportation infrastructure in this analysis.

Risk preferences may be another factor driving land allocation decisions, particularly if fallowing is a risk-mitigating factor of production. The bio-economic model of Zona Bragantina agriculture predicts that higher risk aversion leads to increased reliance on fallow as an alternative to fertilizer and continuous cropping, which tend to produce higher but more variable yields (Borner 2005). Risk-averse farmers may also fallow more land than optimal due to the difficulty in transitioning from continuous cultivation back to a fallow rotation system once the roots crucial for secondary fallow vegetation regeneration have been removed. Collecting forest products may serve as a risk mitigation strategy, though the contribution of fallow to forest product income is already accounted for in the measure of over-fallowing. Wealthier farmers, more able to absorb shocks, often invest in riskier but more lucrative activities than small farmers (Bardhan and Udry 1999, Binswanger and Rosensweig 1993). Farmers with access to perfect credit and insurance markets are also less vulnerable to shocks and can engage in activities generating more variable income. I cannot control for variation in risk preferences or production risk explicitly due to data limitations. However, the liquidity indicators discussed above may also be negatively associated with risk aversion.

Other possible determinants of fallow management efficiency include agroecological factors. Variation in soils and slopes may make fallowing more attractive on certain farms than others; land management that may initially appear as over-fallowing may be an optimal response to poor soil quality. Other studies from the Amazon (Chomitz and Thomas 2003, Pfaff 1999) and elsewhere (Cropper, Puri, and Griffiths 2001, Chomitz and Gray 1996, Nelson and Hellerstein 1997, Deininger and Minten 2002) show that deforestation is more likely to occur on land with good quality soil and faltter slopes. In addition, education and extension assistance may affect fallow management if they play a role in farmer management ability and access to information about new technologies. However, soil quality, farmer education, and extension assistance variables were included in estimating the parameters used to construct the net elasticity of cultivated land measure and therefore cannot be included as right hand side variables in this analysis without raising serious econometric concerns.

6.1.1 Econometric issues

The net elasticity of cultivated land is measured with error because of its construction using estimated parameters from the econometric analyses in Chapter 4. However, measurement error in the dependent variable is subsumed by the error term of the equation (Greene 2000). Thus, as long as the explanatory variables are unrelated to the measurement error of the constructed over-fallowing variable, least squares estimates are consistent despite the measurement error problem. The net elasticity of land is undefined for farms that allocate no land to fallow, so I must exclude 14% of farms from the analysis.

6.1.2 Results

Results for the least squares estimation of the net elasticity of land are given in Table 6.2. I report four sets of estimates corresponding to the four optimal fallowing variables reported in Table 6.1, which I derive using the parameters from Models (1)-(4) of the crop and forest product equations discussed in Chapter 4. The included variables explain a relatively low proportion of the variation in the net elasticity of cultivated land, as seen in R-squared statistics of 0.04-0.05.

Of particular interest are the effects of the liquidity indicators on fallowing. Use of commercial credit is negatively and significantly correlated with the net elasticity of cultivated land across all four models. In addition, higher wage income leads to a significant decrease in the over-fallowing measure. Non-wage income has a significant though not significant effect on the elasticity, which is puzzling in light of the strong negative effects of credit and wage income on fallow management.

These results suggest that liquidity constraints may play a role in restricting farmers' opportunities for expanding cultivated land at the expense of fallow, whether through purchasing sufficient inputs, investing in capital or infrastructure, or other channels. In addition, the links between credit use and off-farm wage income and the net elasticity of cultivated land may provide some evidence for the hypothesis that risk aversion leads to additional fallowing if credit and wage income are indeed correlated with risk preferences. Experimental data on credit access would be ideal to clearly identify the impact of liquidity constraints on fallow management. Any new government-sponsored credit programs in the study region (e.g., Proambiente or an expansion of FNO funding) would offer a good opportunity to collect such data if it is introduced to a random sample of eligible participants before it is widely implemented.

Table 6.2 Net elasticity of cultivated land (over-fallowing) equation

	(1)	(2)	(3)	(4)
Commercial credit use (binary)	-0.492**	-0.664**	-0.487**	-0.844**
	[0.238]	[0.303]	[0.224]	[0.328]
Off-farm wage income (binary)	-0.434**	-0.541*	-0.369*	-0.538*
	[0.219]	[0.279]	[0.203]	[0.296]
Other off-farm income (binary)	-0.204	-0.306	-0.147	-0.276
	[0.221]	[0.282]	[0.206]	[0.301]
Distance from local market	-0.007	-0.009	-0.003	-0.008
	[0.009]	[0.011]	[0.008]	[0.012]
Transportation frequency	-0.006	-0.002	-0.015	-0.01
	[0.085]	[0.109]	[0.076]	[0.113]
Constant	0.792*	0.868	0.707*	0.858
	[0.455]	[0.579]	[0.408]	[0.592]
Observations	205	205	223	233
R-squared	0.05	0.05	0.04	0.05

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Surprisingly, transportation indicators have no significant effect on the net elasticity of cultivated land across all models. Neither the household's distance from local markets nor the village-level transportation frequency affect land allocation efficiency. These findings contrast those from other studies showing a strong link between roads and deforestation, but such results may apply only to virgin forest contexts rather than long-settled regions like the Zona Bragantina where proximity to regional markets is relatively strong and agriculture is already semi-commercialized. Those results also apply to actual deforestation rather than the efficiency of the allotment of land to forest, which may account for the different findings in this study.

These empirical findings are consistent with predictions from the theory that liquidity constraints serve to limit overexploitation of fallow biomass resources. Because biomass most likely does provide positive externalities to downstream farms, these liquidity constraints may act as a second-best option to keep excessive land clearing in check and prevent loss of community income due to diminished hydrological services from forest cover. Liquidity constraints, particularly if severe, can decrease social welfare, however, so shying from economic development that would bring improved credit infrastructure and employment opportunities to the region is not likely to be a desirable strategy in meeting the objectives of poverty alleviation and environmental protection. In addition, because the externality appears to flow upstream to downstream, loosening liquidity constraints may have different implications for social welfare depending on where currently-constrained farms are located within the sub-watershed.

7 Summary, policy implications, and conclusions

Fallow makes an important contribution to farm output in semi-commercial, smallholder agriculture in the Zona Bragantina, a region with similar agroecological conditions and a somewhat more developed infrastructure than other frontier regions in Brazil where shifting cultivation is a mainstay of the economy. Fallowing provides ecological services to farmers by improving land quality, and serves as a source of harvestable products. The ecological literature also suggests that forest fallow provides not only ecological services of global value by sequestering carbon and providing habitat for tropical biodiversity, but offers locally valuable hydrological services as well.

My econometric analysis finds evidence to support the latter claim by indicating that fallow is associated with higher agricultural revenues downstream. Both on-farm and upstream fallow are correlated with higher yields of crops and forest products, and hence higher farm incomes. Thus, farming communities may have some self-interest in preserving forest cover locally, even if transition to permanent cultivation becomes more attractive in the future. I do not find evidence of strategic behavior in land use in response to these positive externalities; that is, farmers do not significantly expand or contract the area they allocate to fallow to take advantage of ecological services provided by their neighbors' forest cover.

While most farmers allocate land efficiently, a substantial minority of farms over-fallow from a private perspective. Farms that could generate more farm income by reallocating land from fallow to cultivation share certain characteristics—they earn significantly less income from off-farm activities and are significantly less likely to use credit, suggesting that liquidity constraints present a barrier to expanding cultivation, even in the relatively developed Zona Bragantina. A pilot approach introducing any new credit programs to a random sample of eligible participants would provide opportunities for a more conclusive study of the liquidity-land use link. Land use that appears as over-fallowing may be justified to some extent by the challenging agroecological conditions documented by agronomists in the Zona Bragantina, particularly on farms lacking high-quality black clay soil.

Because forest fallow appears to provide important local externalities, privately optimal land allocation may be insufficient to ensure that the optimal level of hydrological services reaches downstream farmers. Thus, forest externalities may justify collective management to encourage higher levels of forest cover than those currently maintained by farmers. In addition, removing liquidity constraints or other barriers to agricultural intensification may have ambiguous implications for community-level income, depending on the magnitude of the externality effect.

7.1 Implications for tropical forest policy

The findings on secondary forest externalities and the role of liquidity constraints in land use have potentially important implications for policy-makers pursuing the objectives of poverty alleviation and forest conservation in the Amazon. I consider a few key policy options suggested by the Brazilian government, the international community, and researchers to promote sustainable development. In particular, I discuss the implications of my findings for expansion of current smallholder credit programs, the new Proambiente credit program, a tax on slash-and-burn, and direct subsidy payments for forest conservation. Borner (2005) also discusses these policy options, among others, in the context of his linear programming model of the Zona Bragantina over the next 25 years.

Expanding access to the current FNO credit scheme, which provides loans of up to $B5000 per farmer at 6% interest, is one option to alleviate liquidity constraints in the region. FNO loans have proven inaccessible to many small-scale farmers, as they are often approved on the basis of adoption of specific perennial crops and past use of extension services. Infusing the program with additional funds and loosening collateral and technology adoption requirements may improve farmers' access to loans, allowing for expanded cultivation within the existing shifting cultivation system. Such agricultural intensification could have direct benefits to farmers but also risks indirect community-level costs by decreasing forest hydrological services. Thus, the net effect of this option for smallholders remains ambiguous.

The new Proambiente program, still in pilot phase, provides an alternative opportunity to expand credit access for smallholders. However, the improved loan terms and subsidized technical assistance come with several restrictions on land use. The program promotes riparian reforestation, chop-and-mulch land preparation, and permanent forest set-asides, and prohibits chemical fertilizer use and slash-and-burn. While these practices are likely to promote increased forest and fallow area, farmer income is likely to fall unless the value of increased hydrological services is sufficient to outweigh the losses in income due to decreased use of fertilizer and cultivated land. Indeed, Borner (2005) predicts decreases in farmer welfare, though some gains in fallow area at least meet the environmental objectives of the program. In addition, my findings on the role of liquidity in land management imply that Proambiente could exacerbate inequalities between unconstrained farmers who allocate land efficiently from a private perspective and constrained farmers who use the program to gain access to capital but are restricted in the technologies that they can adopt and ultimately the amount of land they can cultivate profitably.

Taxes on slash-and-burn land preparation are another policy tool with important ramifications for income and land use. This tax would promote the chop-and-mulch land preparation technology purported to avoid the environmental and social costs associated with burning. Large subsidies are likely necessary to promote adoption of this technology without significant loss of farmer incomes (Borner 2005). In addition, the gains in terms of carbon storage are minimal in the long run, as decaying mulch eventually releases carbon to the atmosphere, albeit at a much slower rate than biomass burning. This tax seems poised to exacerbate liquidity constraints, which may lead to increased fallow area but lower farmer incomes. The tax may also create perverse incentives for farmers to transition entirely away from shifting cultivation to permanent cropping, which in the short run may boost forest cover, but in the long run is likely to diminish land under secondary forest and consequently, the amount of carbon stored in above- and below-ground biomass.

Direct payments to farmers for conserving forest or fallow on a per-hectare basis provide a more promising solution to raise incomes while expanding forest cover. Such a subsidy could theoretically be set at a level to achieve the socially optimal allocation of land between cultivation and fallow. It could also serve to alleviate liquidity constraints hindering optimal input use, leading to a first-best outcome for the community income. Borner (2005) estimates the minimum payment necessary to spur farmers to set aside forested area to be $B100/ha. Since forest cover provides local externalities to farmers flowing upstream to downstream, the payments could even be varied based on farms' positions with the watershed to promote optimal forest cover patterns. While such a program will no doubt be expensive to fund, direct payments for forest land may be the approach with the most potential to achieve the elusive "win-win" scenario for tropical forest livelihoods.

7.2 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 biomass provides economically important services to farmers, both as on-site benefits and as positive externalities to sites downstream. The international community also has an interest in preserving forest fallow as a carbon sink that may help mitigate global climate change. Policy options targeting farmers in tropical forested areas may have unanticipated effects due to local externalities, as well as liquidity constraints that appear to affect current land-use patterns. Policy-makers must consider both direct and indirect effects of programs designed to alleviate poverty and conserve forest cover to help ensure that they will meet the desired objectives.

Appendix A: Comparative statics derivations

Case 1

To derive the steady state comparative statics for Case 1, I first substitute out μ using the expression in equation (6). Concentrating the problem in x-η space, the Jacobian J is $\begin{bmatrix} H_{xx} & H_{x\eta} \\ -\dfrac{\eta}{\overline{X}} & -\dfrac{x}{\overline{X}} \end{bmatrix}$

the determinant of which is assumed positive to ensure that sufficiency conditions for a maximum are met. Differentiating with respect to the parameters of interest, and using Cramer's rule, the first order condition (2), and the steady state relationship $\theta = \dfrac{b\overline{X}}{x}(\overline{X} - x)$, yields the following comparative statics results with respect to x and θ.

$$\frac{dx}{dp} = \frac{x\left(F_{14}^{i} - \eta\overline{X}\,(F_{24}^{i} + \sum_{i \neq j} F_{34}^{j})(r+1) \Big/ (r\overline{X} + x) \right)}{\overline{X}|J|} = ?$$

$$\frac{d\theta}{dp} = -\frac{b\overline{X}\left(F_{14}^{i} - \eta\overline{X}\,(F_{24}^{i} + \sum_{i \neq j} F_{34}^{j})(r+1) \Big/ (r\overline{X} + x) \right)}{x|J|} = ?$$

$$\frac{dx}{dq} = -\frac{\eta x\,(V_{13}^{i} + \sum_{i \neq j} V_{23}^{j})(1+r) \Big/ (r\overline{X} + x)}{|J|} < 0$$

$$\frac{d\theta}{dq} = \frac{\eta b\overline{X}^{2}\,(V_{13}^{i} + \sum_{i \neq j} V_{23}^{j})(1+r) \Big/ (r\overline{X} + x)}{x|J|} > 0$$

$$\frac{dx}{dr} = \frac{x\eta\mu}{(r + x/\overline{X})\,\overline{X}^{2}|J|} > 0$$

$$\frac{d\theta}{dr} = -\frac{b\overline{X}\eta\mu}{(r + x/\overline{X})\,\overline{X}x|J|} < 0$$

$$\frac{dx}{dA} = \frac{x\left(F_{15}^{i} - \eta\bar{X}\,(F_{25}^{i} + \sum_{i\neq j} F_{35}^{j})(r+1)\Big/(r\bar{X}+x)\right)}{\bar{X}|J|} = ?$$

$$\frac{d\theta}{dA} = -\frac{b\bar{X}\left(F_{15}^{i} - \eta\bar{X}\,(F_{25}^{i} + \sum_{i\neq j} F_{35}^{j})(r+1)\Big/(r\bar{X}+x)\right)}{x|J|} = ?$$

$$\frac{dx}{db} = -\frac{H_{x\eta}}{|J|} = ?$$

$$\frac{d\theta}{db} = \bar{X}\left(\frac{\bar{X}}{x} - 1\right) + \frac{b\bar{X}^{2}H_{x\eta}}{x^{2}|J|} = ?$$

$$\frac{dx}{d\theta_{j\neq i}} = \frac{x\left(\sum_{i\neq j} F_{13}^{i} - \eta\bar{X}(\sum_{i\neq j} V_{12}^{i} + V_{22}^{j} + \sum_{i\neq j} F_{23}^{i} + F_{33}^{j})\,(r+1)\big/(r\bar{X}+x)\right)}{\bar{X}|J|} = ?$$

$$\frac{d\theta}{d\theta_{j\neq i}} = -\frac{b\bar{X}\left(\sum_{i\neq j} F_{13}^{i} - \eta\bar{X}(\sum_{i\neq j} V_{12}^{i} + V_{22}^{j} + \sum_{i\neq j} F_{23}^{i} + F_{33}^{j})\,(r+1)\big/(r\bar{X}+x)\right)}{x|J|} = ?$$

$$\frac{dx}{dw} = \frac{x\left(F_{16}^{i} - \eta\bar{X}(V_{14}^{i} + \sum_{j\neq i} \eta V_{24}^{j} + F_{26}^{i} + \sum_{j\neq i} \eta F_{36}^{j})\,(1+r)\big/(r\bar{X}+x))\right)}{\bar{X}|J|} = ?$$

$$\frac{d\theta}{dw} = -\frac{b\bar{X}\left(F_{16}^{i} - \eta\bar{X}(V_{14}^{i} + \sum_{j\neq i} \eta V_{24}^{j} + F_{26}^{i} + \sum_{j\neq i} \eta F_{36}^{j})\,(1+r)\big/(r\bar{X}+x))\right)}{x|J|} = ?$$

$$\frac{dx}{dv} = \frac{x\left(F_{17}^{i} - \eta\bar{X}(F_{27}^{i} + \sum_{j\neq i} F_{37}^{j})(1+r)\Big/(r\bar{X}+x)\right)}{\bar{X}|J|} = ?$$

$$\frac{d\theta}{dv} = -\frac{b\bar{X}\left(F_{17}^{i} - \eta\bar{X}(F_{27}^{i} + \sum_{j\neq i} F_{37}^{j})(1+r)\Big/(r\bar{X}+x)\right)}{x|J|} = ?$$

To derive the comparative statics of x and θ with respect to p, A, and v assuming Cobb-Douglas functional forms for crops and forest products, I rewrite the net revenue functions for crops and forest products (maximized with respect to labor and fertilizer) as

$$V^i = \left(q\theta_i^{\alpha_1} \sum_{j \neq i} \theta_j^{\alpha_2} w^{-\delta} \delta^{\delta} \right)^{\frac{1}{1-\delta}}$$

$$F^i = \left(pAx_i^{\beta_1} \theta_i^{\beta_2} \sum_{j \neq i} \theta_j^{\beta_3} w^{-\gamma_1} v^{-\gamma_2} \gamma_1^{\gamma_1} \gamma_2^{\gamma_2} \right)^{\frac{1}{1-\gamma_1-\gamma_2}}$$

Assuming $1-\gamma_1-\gamma_2 > 0$, the comparative statics then become

$$\frac{dx}{dp} = \frac{x\gamma_2 \left(\beta_1 F^i \big/ x - \overline{X}(1+r)(\beta_2 F^i + \beta_3 \sum_{j \neq i} F^j) \big/ ((r\overline{X}+x)(\overline{X}-x)) \right)}{\overline{X}p(1-\gamma_1-\gamma_2)^2 |J|} > 0$$

$$\frac{d\theta}{dp} = -\frac{b\overline{X}\gamma_2 \left(\beta_1 F^i \big/ x - \overline{X}(1+r)(\beta_2 F^i + \beta_3 \sum_{j \neq i} F^j) \big/ ((r\overline{X}+x)(\overline{X}-x)) \right)}{xp(1-\gamma_1-\gamma_2)^2 |J|} < 0$$

$$\frac{dx}{dA} = \frac{x\gamma_2 \left(\beta_1 F^i \big/ x - \overline{X}(1+r)(\beta_2 F^i + \beta_3 \sum_{j \neq i} F^j) \big/ ((r\overline{X}+x)(\overline{X}-x)) \right)}{\overline{X}A(1-\gamma_1-\gamma_2)^2 |J|} > 0$$

$$\frac{d\theta}{dA} = -\frac{b\overline{X}\gamma_2 \left(\beta_1 F^i \big/ x - \overline{X}(1+r)(\beta_2 F^i + \beta_3 \sum_{j \neq i} F^j) \big/ ((r\overline{X}+x)(\overline{X}-x)) \right)}{xA(1-\gamma_1-\gamma_2)^2 |J|} < 0$$

$$\frac{dx}{dv} = -\frac{x\gamma_2 \left(\beta_1 F^i \big/ x - \overline{X}(1+r)(\beta_2 F^i + \beta_3 \sum_{j \neq i} F^j) \big/ ((r\overline{X}+x)(\overline{X}-x)) \right)}{\overline{X}v(1-\gamma_1-\gamma_2)^2 |J|} < 0$$

$$\frac{d\theta}{dv} = \frac{b\overline{X}\gamma_2 \left(\beta_1 F^i \big/ x - \overline{X}(1+r)(\beta_2 F^i + \beta_3 \sum_{j \neq i} F^j) \big/ ((r\overline{X}+x)(\overline{X}-x)) \right)}{xv(1-\gamma_1-\gamma_2)^2 |J|} > 0$$

Case 3

Here I present comparative statics with respect to the credit and off-farm employment constraints and the wage rate when liquidity constraints are binding. In this case, farmers maximize profits individually, not considering the value of fallow externalities. I assume a Cobb-Douglas functional form, substituting in the equalities $z = R + \frac{wM}{v}$ and $l_h = M - L - l_c$ for fertilizer and forest product labor, respectively. The Hamiltonian for the problem becomes

$$H = \sum_{i}^{N}\left\{ qh^{i}\left(\theta_i, \sum_{j}^{N_i}\theta_j, L - M - l_{ci}\right) + pAf^{i}\left(x_i, \theta_i, \sum_{j}^{N_i}\theta_j, l_{ci}, R + \frac{wM}{V}\right) - cx_i\eta_i + wM \right\}$$

$$+ \mu\left(b - \frac{\eta_i x_i}{\bar{X}_i}\right)$$

The Jacobian J for this problem is $\begin{bmatrix} H_{xx} & H_{xl_c} & H_{x\eta} \\ H_{xl_c} & H_{l_c l_c} & H_{l_c\eta} \\ -\frac{\eta}{\bar{X}} & 0 & -\frac{x}{\bar{X}} \end{bmatrix}$

the determinant of which is negative, satisfying conditions for concavity. The comparative statics for the relevant parameters are

$$\frac{dx}{dM} = \frac{x\left(H_{xM}H_{l_c l_c} - H_{xl_c}H_{l_c M}\right)}{\bar{X}|J|} = ?$$

$$\frac{d\theta}{dM} = -\frac{b\bar{X}\left(H_{xM}H_{l_c l_c} - H_{xl_c}H_{l_c M}\right)}{x|J|} = ?$$

$$\frac{dx}{dw} = \frac{x\left(H_{xw}H_{l_c l_c} - H_{xl_c}H_{l_c w}\right)}{\bar{X}|J|} > 0$$

$$\frac{d\theta}{dw} = -\frac{b\bar{X}\left(H_{xw}H_{l_c l_c} - H_{xl_c}H_{l_c w}\right)}{x|J|} < 0$$

$$\frac{dx}{dR} = \frac{x\left(H_{xR}H_{l_c l_c} - H_{xl_c}H_{l_c R}\right)}{\bar{X}|J|} > 0$$

$$\frac{d\theta}{dR} = -\frac{b\bar{X}\left(H_{xR}H_{l_c l_c} - H_{xl_c}H_{l_c R}\right)}{x|J|} < 0$$

where

$$H_{xM} = \frac{\alpha_1 \delta q \eta \overline{X}(1+r)V^i}{\theta(L-M-l_c)(r\overline{X}+x)} + \frac{\beta_1 \gamma_2 wpA\eta \overline{X}F^i}{xv(R+wM/v)} - \frac{\beta_2 \gamma_2 pwA\eta \overline{X}(1+r)F^i}{\theta v(R+wM/v)(r\overline{X}+x)} > 0$$

$$H_{l_c l_c} = (\delta(1-\delta)qV^i)\big/(L-M-l_c)^2 + \gamma(1-\gamma)pAF^i\big/l_c^2 < 0$$

$$H_{xl_c} = \frac{\delta}{(L-M-l_c)}\left(\alpha_1 q\eta V^i/\theta - \beta_1 pAF^i/x - \beta_2 pAF^i/\theta\right) > 0$$

$$H_{l_c M} = \frac{\delta(1-\delta)qV^i}{(L-M-l_c)} + \frac{w\gamma_1\gamma_2 pAF^i}{vl_c(R+wM/v)} = ?$$

$$H_{xR} = \frac{\beta_1\gamma_2 pA\eta\overline{X}F^i}{x(R+wM/v)} - \frac{\beta_2\gamma_2 pA\eta\overline{X}(1+r)F^i}{\theta(R+wM/v)(r\overline{X}+x)} > 0$$

$$H_{l_c R} = \frac{\gamma_1\gamma_2 pAF^i}{l_c(R+wM/v)} < 0$$

$$H_{xw} = \frac{\beta_1\gamma_2 pAM\eta\overline{X}F^i}{xv(R+wM/v)} - \frac{\beta_2\gamma_2 pAM\eta\overline{X}(1+r)F^i}{\theta v(R+wM/v)(r\overline{X}+x)} > 0$$

$$H_{l_c w} = \frac{\gamma_1\gamma_2 pAMF^i}{l_c v(R+wM/v)} < 0$$

Appendix B

Table B1. First stage OLS regressions for on- and off-farm fallow used in crop production equations

	Model 2		Model 4	
	Log of fallow area	Log of upstream fallow area – survey data	Log of fallow area	Log of upstream canopy cover – GIS data, 3km radius
Log cultivated area	-0.038	-0.012	-0.006	-0.01
	[0.087]	[0.025]	[0.080]	[0.011]
Log family labor	-0.175**	0.02	-0.086	-0.006
	[0.083]	[0.023]	[0.075]	[0.010]
Log hired labor	0.002	-0.027*	0	0.003
	[0.056]	[0.016]	[0.051]	[0.007]
Log chemical fertilizer	0.023	-0.021	0.027	-0.014**
	[0.052]	[0.015]	[0.046]	[0.006]
Perennial producer (binary)	-0.053	-0.117***	-0.09	-0.014
	[0.154]	[0.043]	[0.143]	[0.019]
Use extension services (binary)	-0.031	0.035	-0.038	0.005
	[0.156]	[0.044]	[0.141]	[0.019]
Household head's schooling years	-0.006	0.001	-0.004	0.005*
	[0.023]	[0.006]	[0.021]	[0.003]
Farm owner (binary)	0.133	-0.032	0.147	0.030*
	[0.134]	[0.038]	[0.123]	[0.017]
Black clay soil (binary)	-0.246	-0.122**	-0.186	-0.004
	[0.217]	[0.061]	[0.203]	[0.030]
Charcoal-enriched soil (binary)	-0.022	-0.034	-0.053	0.002
	[0.183]	[0.052]	[0.181]	[0.025]
Poor soil (binary)	0.061	-0.069	-0.017	-0.005
	[0.283]	[0.080]	[0.255]	[0.034]
Slope	0.074**	0.025**	0.039	0.003
	[0.036]	[0.010]	[0.035]	[0.005]
No on-farm fallow (binary)	-1.884***	0.021	-1.840***	-0.025
	[0.213]	[0.060]	[0.187]	[0.025]
No family labor (binary)	-0.808	0.215	-0.177	0.08
	[0.571]	[0.161]	[0.539]	[0.074]
No hired labor (binary)	-0.016	-0.152**	0.041	-0.006
	[0.242]	[0.068]	[0.219]	[0.030]
No fertilizer (binary)	0.106	-0.069	0.141	-0.026
	[0.280]	[0.079]	[0.242]	[0.034]
No upstream fallow (binary)	1.177**	-1.423***		
	[0.491]	[0.139]		
Log of farm size	0.856***	-0.032*	0.743***	0.012
	[0.063]	[0.018]	[0.058]	[0.008]

Forest product prices (farm-level)	0.005	0	0.008**	0
	[0.004]	[0.001]	[0.004]	[0.001]
Own firewood stove (binary)	-0.133	-0.005	-0.067	0.056**
	[0.169]	[0.048]	[0.160]	[0.022]
Own gas stove (binary)	-0.048	-0.016	0.002	-0.013
	[0.170]	[0.048]	[0.160]	[0.022]
Log of farm size – upstream weighted average[32]	-0.058	0.512***	-0.102	0.039***
	[0.143]	[0.040]	[0.078]	[0.010]
Forest product price – upstream weighted average	-0.016	0.016**	-0.010***	0.001
	[0.025]	[0.007]	[0.004]	[0.001]
Own firewood stove – upstream weighted average	0.422	0.432***	0.325	0.275***
	[0.538]	[0.152]	[0.343]	[0.046]
Own gas stove – upstream weighted average	-0.035	-0.483***	-0.097	0.042
	[0.568]	[0.160]	[0.276]	[0.037]
Use extension service – upstream weighted average	-0.495	0.085	-0.244	-0.136***
	[0.381]	[0.108]	[0.269]	[0.036]
Household head schooling – upstream weighted ave.	-0.04	-0.012	-0.165	0.039*
	[0.079]	[0.022]	[0.151]	[0.021]
Farm owner – upstream weighted average	0.2	-0.119	0.036	0.092***
	[0.408]	[0.115]	[0.242]	[0.034]
Black clay soil – upstream weighted average	-0.536	-1.161***	-0.167	-0.022
	[0.658]	[0.186]	[0.314]	[0.042]
Charcoal-enriched soil – upstream weighted average	-0.326	-0.159	-0.336	-0.119***
	[0.602]	[0.170]	[0.278]	[0.038]
Poor soil – upstream weighted average	0.132	-0.026	-0.166	0.005
	[0.540]	[0.153]	[0.401]	[0.055]
Slope – upstream weighted average	-0.041	-0.012	-0.032	0.016***
	[0.043]	[0.012]	[0.040]	[0.005]
Castanhal municipality	0.243	-0.175*	0.096	-0.182***
	[0.328]	[0.093]	[0.228]	[0.031]
Igarapé Açu municipality	0.044	-0.253**	0.222	-0.108***
	[0.365]	[0.103]	[0.217]	[0.029]
Constant	0.602	1.934***	0.909	2.954***
	[0.810]	[0.229]	[0.657]	[0.089]
Observations	235	235	270	260

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[32] The upstream neighborhood for each model corresponds to the respective upstream off-farm fallow definition: the neighborhood for Model 2 is all upstream households, while the neighborhood for Model 4 is upstream area within a 3km radius.

R-squared	0.75	0.91	0.74	0.76

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Table B2. Instrumental variables validity checks: p-values from including each instrument individually in the crop production equation

	Model 2	Model 4
Log of farm size	0.94	0.93
Forest product prices (farm-level)	0.22	0.21
Own firewood stove (binary)	0.90	0.69
Own gas stove (binary)	0.60	0.27
Log of farm size – upstream weighted average[33]	0.46	0.83
Forest product price – upstream weighted average	0.87	0.56
Own firewood stove – upstream weighted average	0.21	0.64
Own gas stove – upstream weighted average	0.16	0.41
Use extension service – upstream weighted average	0.62	0.77
Household head schooling – upstream weighted ave.	0.73	0.18
Farm owner – upstream weighted average	0.73	0.64
Black clay soil – upstream weighted average	0.48	0.27
Charcoal-enriched soil – upstream weighted average	0.78	0.98
Poor soil – upstream weighted average	0.72	0.90
Slope – upstream weighted average	0.99	0.97
Sargan test for overidentification	0.95	0.90
Hausman Chi-2 test for joint exogeneity of on- and off-farm fallow	0.87	0.55

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[33] The upstream neighborhood for each model corresponds to the upstream off-farm fallow definition: the neighborhood for Model 2 is all upstream households, while the neighborhood for Model 4 is upstream area within a 3km radius.

Table B3. Robustness analysis: crop production function excluding observations from top and bottom 10 percentiles of on-farm fallow and upstream fallow area

	Full sample	Excluding farms with no on-farm fallow area	Excluding top 10% of on-farm fallow area	Excluding bottom 10% of upstream fallow	Excluding top 10% of upstream fallow area
Log on-farm fallow area	0.100	0.111*	0.081	0.097	0.087
	[0.060]	[0.060]	[0.068]	[0.062]	[0.067]
Log off-farm fallow – survey fallow area	0.367**	0.322*	0.374**	0.204	0.507***
	[0.166]	[0.170]	[0.173]	[0.292]	[0.192]
Log cultivated area	0.412***	0.447***	0.381***	0.371***	0.380***
	[0.104]	[0.111]	[0.110]	[0.111]	[0.113]
Log family labor	0.127	0.168	0.14	0.182*	0.117
	[0.098]	[0.107]	[0.102]	[0.106]	[0.102]
Log hired labor	0.177**	0.124*	0.197***	0.197***	0.187**
	[0.068]	[0.074]	[0.072]	[0.074]	[0.073]
Log chemical fertilizer	0.147**	0.179***	0.147**	0.114*	0.154**
	[0.058]	[0.064]	[0.061]	[0.068]	[0.061]
Perennial producer (binary)	0.913***	0.875***	0.983***	0.964***	0.903***
	[0.186]	[0.197]	[0.196]	[0.198]	[0.194]
Use extension services (binary)	0.264	0.246	0.208	0.193	0.31
	[0.186]	[0.189]	[0.200]	[0.202]	[0.200]
Household head schooling years	-0.02	-0.026	-0.019	-0.015	-0.03
	[0.026]	[0.027]	[0.027]	[0.028]	[0.027]
Farm owner (binary)	0.07	0.073	0.091	0.116	0.071
	[0.165]	[0.175]	[0.177]	[0.176]	[0.179]
Black clay soil (binary)	0.225	0.207	0.27	0.2	0.136
	[0.248]	[0.252]	[0.274]	[0.276]	[0.281]
Charcoal-enriched soil (binary)	0.375*	0.414*	0.364	0.371	0.346
	[0.226]	[0.228]	[0.233]	[0.239]	[0.235]
Poor soil (binary)	-0.123	0.074	-0.099	-0.203	-0.057
	[0.325]	[0.366]	[0.333]	[0.362]	[0.334]
Slope	-0.01	-0.019	-0.022	-0.015	0.027
	[0.029]	[0.030]	[0.031]	[0.033]	[0.036]
Castanhal municipality (binary)	0.255	0.214	0.175	0.233	0.177
	[0.239]	[0.249]	[0.256]	[0.258]	[0.263]
Igarapé Açu municipality (binary)	0.285	0.2	0.211	0.259	0.209
	[0.240]	[0.258]	[0.258]	[0.271]	[0.263]
No on-farm fallow (binary)	0.43		0.389	0.325	0.345
	[0.300]		[0.310]	[0.316]	[0.321]
No upstream	1.109*	0.046	1.086*		1.522**

fallow area (binary)	[0.633]	[1.125]	[0.651]		[0.696]
No family labor (binary)	1.258*	1.406*	1.213*	1.566**	1.183*
	[0.685]	[0.721]	[0.722]	[0.726]	[0.706]
No hired labor (binary)	0.024	-0.133	0.113	-0.001	0.084
	[0.297]	[0.331]	[0.309]	[0.331]	[0.319]
No fertilizer (binary)	0.178	0.221	0.149	0.042	0.234
	[0.324]	[0.353]	[0.340]	[0.367]	[0.359]
Constant	3.437***	3.474***	3.384***	3.848***	3.090***
	[0.665]	[0.698]	[0.699]	[1.066]	[0.719]
Observations	228	199	205	205	207
R-squared	0.6	0.62	0.59	0.59	0.59

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B4. Robustness analysis: crop production function excluding observations from top and bottom 10 percentiles of on-farm fallow and upstream canopy cover

	Full sample	Excluding farms with no on-farm fallow area	Excluding top 10% of on-farm fallow area	Excluding bottom 10% of upstream fallow	Excluding top 10% of upstream fallow area
Log on-farm fallow area	0.099	0.07	0.078	0.101	0.119*
	[0.061]	[0.084]	[0.070]	[0.064]	[0.065]
Log off-farm fallow – 3km upstream GIS canopy cover	0.966**	0.994*	1.043**	0.918*	1.140**
	[0.489]	[0.549]	[0.506]	[0.548]	[0.529]
Log cultivated area	0.442***	0.490***	0.408***	0.426***	0.397***
	[0.099]	[0.109]	[0.104]	[0.103]	[0.102]
Log family labor	0.068	0.127	0.089	0.163	0.07
	[0.093]	[0.106]	[0.097]	[0.100]	[0.096]
Log hired labor	0.187***	0.142**	0.204***	0.169**	0.180***
	[0.064]	[0.070]	[0.067]	[0.068]	[0.067]
Log chemical fertilizer	0.169***	0.184***	0.171***	0.162***	0.162***
	[0.059]	[0.065]	[0.062]	[0.061]	[0.062]
Perennial producer (binary)	0.835***	0.770***	0.892***	0.837***	0.833***
	[0.173]	[0.186]	[0.182]	[0.186]	[0.181]
Use extension services (binary)	0.21	0.304	0.149	0.134	0.279
	[0.173]	[0.185]	[0.185]	[0.187]	[0.182]
Household head schooling years	-0.022	-0.033	-0.022	-0.026	-0.025
	[0.025]	[0.027]	[0.026]	[0.026]	[0.026]
Farm owner (binary)	-0.027	-0.077	-0.002	-0.071	-0.035
	[0.155]	[0.173]	[0.165]	[0.163]	[0.163]
Black clay soil (binary)	0.205	0.27	0.242	0.192	0.107
	[0.245]	[0.257]	[0.270]	[0.239]	[0.264]

Charcoal-enriched soil (binary)	0.378*	0.381	0.369	0.388	0.362
	[0.226]	[0.239]	[0.234]	[0.244]	[0.230]
Poor soil (binary)	0.134	0.352	0.154	0.187	0.142
	[0.295]	[0.332]	[0.301]	[0.302]	[0.305]
Slope	-0.018	-0.028	-0.031	-0.011	0.001
	[0.029]	[0.031]	[0.031]	[0.029]	[0.035]
Castanhal municipality (binary)	0.607**	0.683**	0.548**	0.630**	0.616**
	[0.255]	[0.279]	[0.275]	[0.255]	[0.267]
Igarapé Açu municipality (binary)	0.299	0.317	0.228	0.233	0.271
	[0.226]	[0.245]	[0.245]	[0.228]	[0.246]
No on-farm fallow (binary)	0.531*	0	0.493*	0.587**	0.544*
	[0.275]	[0.000]	[0.288]	[0.293]	[0.287]
No family labor (binary)	0.844	1.095	0.811	1.916**	0.852
	[0.676]	[0.718]	[0.714]	[0.737]	[0.693]
No hired labor (binary)	0.129	0.017	0.208	0.171	0.127
	[0.281]	[0.316]	[0.291]	[0.301]	[0.297]
No fertilizer (binary)	0.303	0.325	0.278	0.265	0.268
	[0.314]	[0.340]	[0.328]	[0.322]	[0.336]
Constant	1.325	1.148	1.007	1.195	0.777
	[1.788]	[2.017]	[1.844]	[1.973]	[1.916]
Observations	251	206	227	221	231
R-squared	0.57	0.6	0.55	0.59	0.56

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Figure B1. On-farm fallow elasticity in crop production and 95% confidence interval, excluding one observation at a time (Model 1)

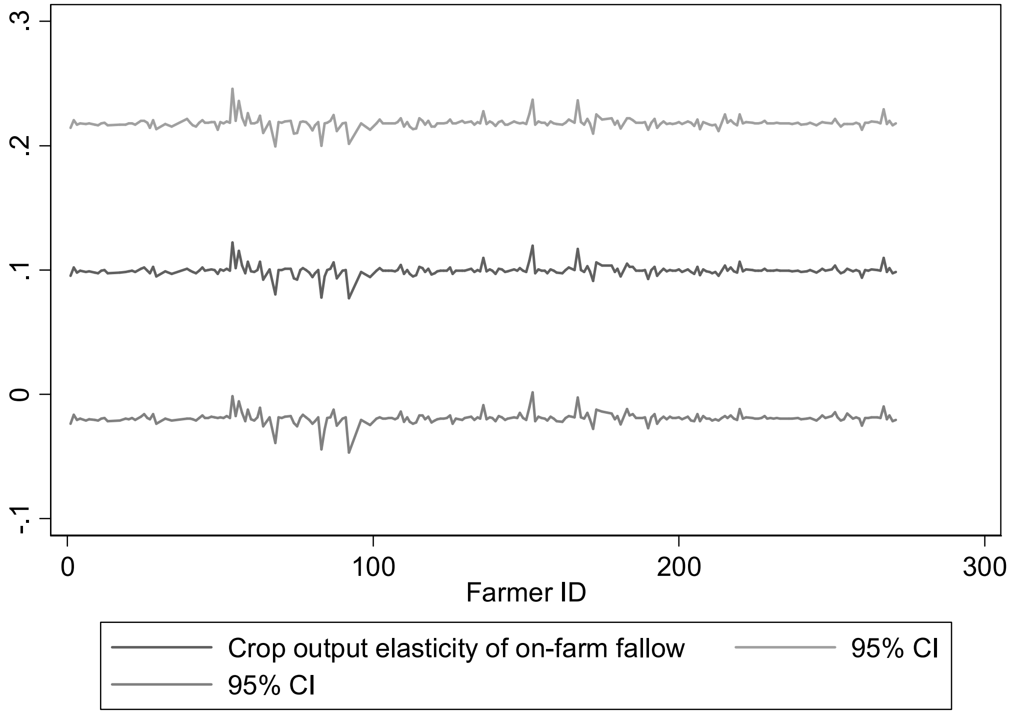

Figure B2. Upstream fallow elasticity in crop production and 95% confidence interval, excluding one observation at a time (Model 1)

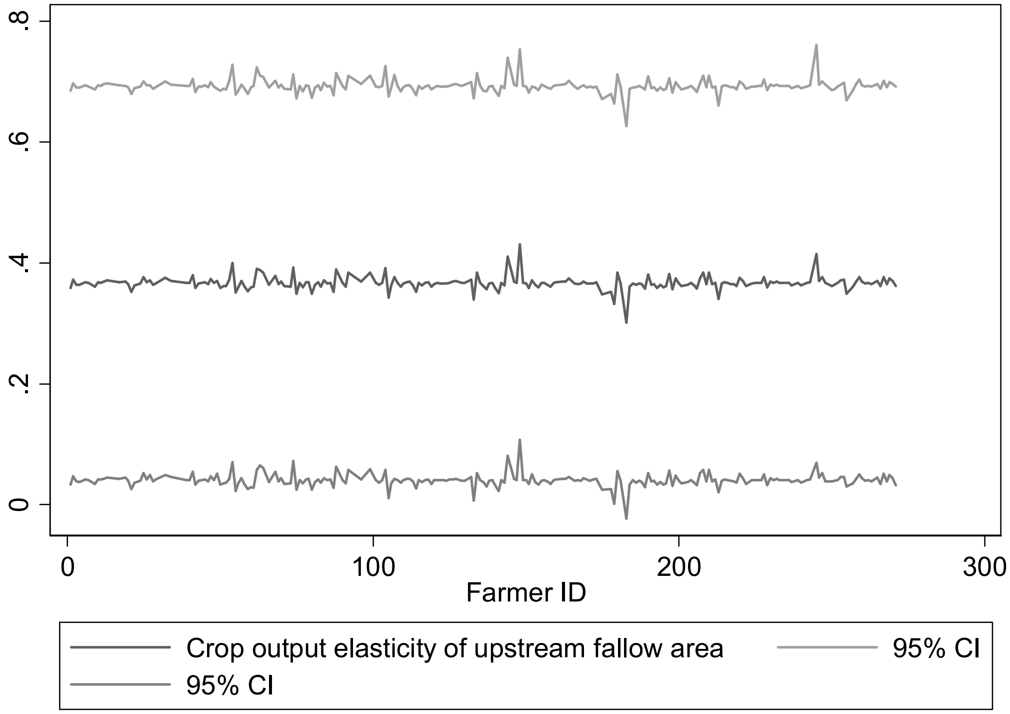

Figure B3. On-farm fallow elasticity in crop production and 95% confidence interval, excluding one observation at a time (Model 3)

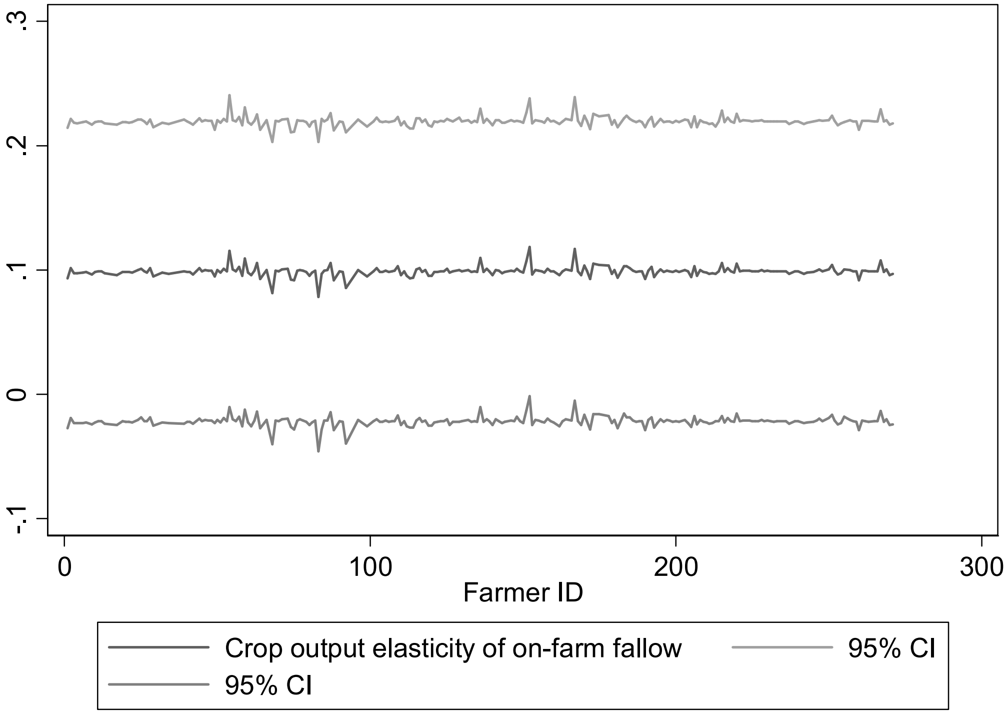

Figure B4. Upstream canopy cover elasticity in crop production and 95% confidence interval, excluding one observation at a time (Model 3)

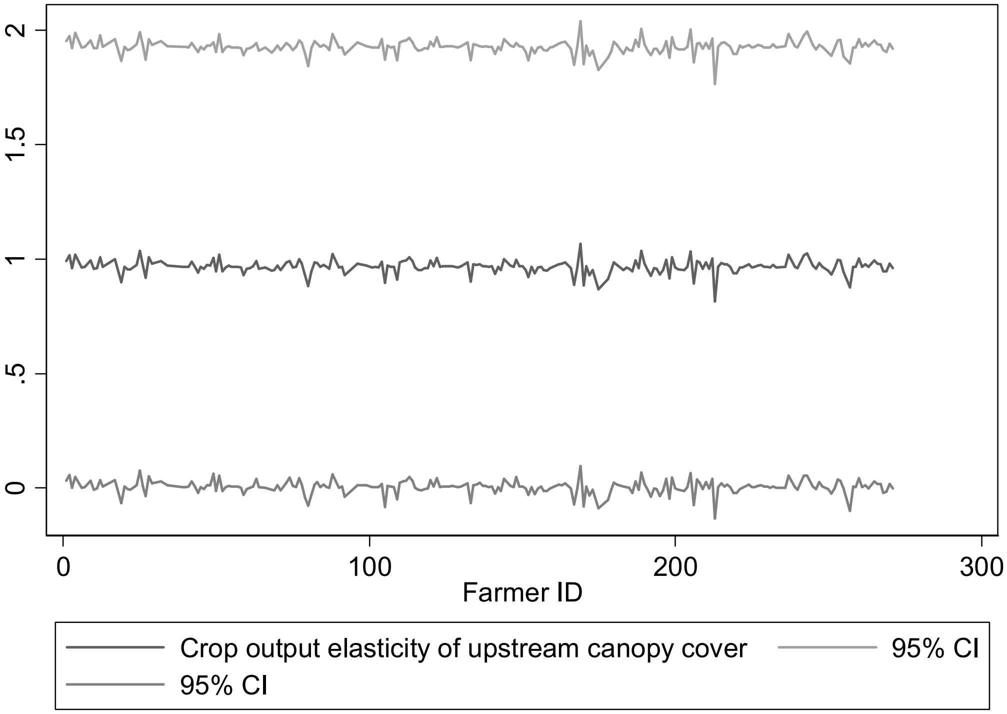

Table B5. Bootstrap bias estimates for crop production function parameters, 500 replications

	Model (1)	Model (2)	Model (3)	Model (4)
On-farm fallow	-0.004	-0.005	0.003	-0.0005
Upstream fallow area	0.003	0.003		
Upstream canopy cover (3km radius)			-0.062	-0.095

Table B6. Crop production function estimation including downstream forest fallow

	SEM (1)	SEM-IV (2)	SEM (3)	SEM-IV (4)
Log on-farm fallow area	0.107*	0.174**	0.099*	0.184**
	[0.058]	[0.079]	[0.059]	[0.089]
Log off-farm fallow – upstream survey fallow area	0.373**	0.403**		
	[0.157]	[0.178]		
Log off-farm fallow – 3 km upstream GIS canopy cover			0.918	0.418
			[0.561]	[1.014]
Log off-farm fallow – downstream survey fallow area	-0.15	-0.302**		
	[0.098]	[0.140]		
Log off-farm fallow – 3 km downstream GIS canopy cover			0.088	0.052
			[0.577]	[1.110]
Log cultivated area	0.423***	0.395***	0.440***	0.422***
	[0.099]	[0.099]	[0.097]	[0.101]
Log family labor	0.132	0.136	0.068	0.078
	[0.093]	[0.093]	[0.089]	[0.090]
Log hired labor	0.166**	0.168***	0.187***	0.173***
	[0.065]	[0.065]	[0.061]	[0.062]
Log chemical fertilizer	0.145***	0.147***	0.170***	0.163***
	[0.055]	[0.055]	[0.057]	[0.059]
Perennial producer (binary)	0.896***	0.907***	0.832***	0.822***
	[0.176]	[0.176]	[0.167]	[0.169]
Use extension services (binary)	0.236	0.242	0.208	0.194
	[0.177]	[0.177]	[0.166]	[0.170]
Household head schooling years	-0.018	-0.019	-0.023	-0.023
	[0.025]	[0.025]	[0.024]	[0.025]
Farm owner (binary)	0.092	0.112	-0.027	-0.006
	[0.157]	[0.157]	[0.149]	[0.151]
Black clay soil (binary)	0.201	0.146	0.211	0.225
	[0.236]	[0.237]	[0.239]	[0.246]
Charcoal-enriched soil (binary)	0.342	0.316	0.381*	0.434*
	[0.215]	[0.216]	[0.217]	[0.225]
Poor soil (binary)	-0.184	-0.198	0.14	0.101
	[0.310]	[0.309]	[0.284]	[0.289]
Slope	-0.013	-0.019	-0.018	-0.009
	[0.027]	[0.027]	[0.027]	[0.030]
Castanhal municipality (binary)	0.238	0.152	0.611**	0.458

	[0.228]	[0.231]	[0.248]	[0.282]
Igarapé Açu municipality (binary)	0.234	0.13	0.299	0.247
	[0.230]	[0.238]	[0.216]	[0.221]
No on-farm fallow (binary)	0.451	0.632*	0.532**	0.690**
	[0.284]	[0.323]	[0.264]	[0.311]
No upstream fallow area (binary)	1.247**	1.387**		
	[0.606]	[0.654]		
No family labor (binary)	1.269**	1.259*	0.848	0.906
	[0.648]	[0.645]	[0.647]	[0.656]
No hired labor (binary)	-0.033	-0.001	0.129	0.069
	[0.284]	[0.282]	[0.270]	[0.275]
No fertilizer (binary)	0.195	0.183	0.305	0.272
	[0.307]	[0.308]	[0.301]	[0.304]
Constant	3.787***	3.968***	1.17	2.792
	[0.805]	[0.851]	[1.972]	[2.527]
Spatial error correlation coefficient	-0.026	-0.045	-0.007	-0.022
(λ)	[0.129]	[0.125]	[0.183]	[0.150]
Observations	228	228	251	251
R-squared	0.60	0.60	0.57	0.56
Log likelihood	-312.65	-311.87	-349.63	-350.73

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B7. Forest product harvesting: Cragg hurdle vs. Tobit models

	Model 1			Model 3		
	Probit	Truncated regression	Tobit	Probit	Truncated regression	Tobit
Log on-farm fallow area	0.243***	0.064	0.595***	0.275***	0.023	0.639***
	[0.091]	[0.109]	[0.190]	[0.089]	[0.113]	[0.197]
Log off-farm fallow –upstream survey fallow area	0.389*	0.559**	1.242**			
	[0.226]	[0.276]	[0.498]			
Log off-farm fallow – 3 km upstream GIS canopy cover				1.086	0.954	2.695*
				[0.736]	[0.831]	[1.550]
Forest product price (village median)	-0.169	0.043	-0.283	0.107	0.157	0.29
	[0.143]	[0.192]	[0.310]	[0.097]	[0.175]	[0.234]
Log household size	0.790***	0.087	1.337***	0.735***	0.227	1.443***
	[0.237]	[0.267]	[0.477]	[0.214]	[0.262]	[0.466]
Agricultural wage rate	-0.201**	0.026	-0.371**	-0.182**	-0.029	-0.363**
	[0.081]	[0.102]	[0.177]	[0.072]	[0.089]	[0.163]
Household head schooling years	0.036	0.035	0.107	0.029	0.074	0.124
	[0.038]	[0.047]	[0.082]	[0.036]	[0.046]	[0.082]
Farm owner (binary)	0.233	-0.192	0.262	0.009	-0.33	-0.248
	[0.253]	[0.270]	[0.497]	[0.222]	[0.273]	[0.486]
Own car (binary)	-0.839**	1.237**	-1.239	-0.748**	1.114**	-1.079
	[0.359]	[0.529]	[0.862]	[0.344]	[0.514]	[0.854]
Own television (binary)	-0.002	0.628**	0.339	0.052	0.697**	0.427
	[0.281]	[0.277]	[0.541]	[0.264]	[0.275]	[0.542]
Use electricity (binary)	-0.672**	-1.041***	-1.850***	-0.670**	-1.031***	-1.845***
	[0.291]	[0.266]	[0.520]	[0.266]	[0.268]	[0.520]
Own firewood stove (binary)	0.238	0.433	1.296*	0.315	0.319	1.462**
	[0.283]	[0.380]	[0.663]	[0.267]	[0.395]	[0.670]
Own gas stove (binary)	-1.157***	-0.011	-1.275**	-0.959**	0.102	-1.035*
	[0.445]	[0.307]	[0.617]	[0.383]	[0.305]	[0.614]

Black clay soil (binary)	0.781*	0.957**	1.798**	0.548	0.749*	1.593**
	[0.441]	[0.408]	[0.781]	[0.388]	[0.402]	[0.783]
Charcoal-enriched soil (binary)	0.184	-0.147	0.287	0.076	-0.453	-0.174
	[0.340]	[0.388]	[0.718]	[0.324]	[0.397]	[0.735]
Poor soil (binary)	-0.325	0.477	-0.186	-0.273	0.63	-0.044
	[0.528]	[0.537]	[1.029]	[0.441]	[0.521]	[0.966]
Slope	-0.009	-0.065	-0.118	-0.018	-0.074	-0.136
	[0.045]	[0.047]	[0.088]	[0.042]	[0.047]	[0.089]
Castanhal municipality (binary)	0.685**	0.661	1.597**	0.755*	0.668	1.772**
	[0.345]	[0.445]	[0.747]	[0.399]	[0.491]	[0.858]
Igarapé Açu municipality (binary)	1.313***	0.268	2.314***	0.849**	-0.067	1.232*
	[0.399]	[0.463]	[0.783]	[0.354]	[0.410]	[0.706]
No on-farm fallow area (binary)	0.249	-0.163	0.515	0.072	-0.095	0.214
	[0.437]	[0.569]	[0.946]	[0.394]	[0.563]	[0.930]
No upstream fallow area (binary)	-2.157*	0.403	-3.729			
	[1.125]	[1.643]	[2.525]			
Constant	0.481	2.415	-0.478	-3.494	0.688	-8.854
	[1.300]	[1.617]	[2.793]	[2.499]	[3.047]	[5.451]
Observations	236	167	236	261	184	261
Log likelihood	-98.25	-293.50	-481.25	-117.53	-331.05	-541.62
Likelihood ratio test of Tobit restriction	0.00			0.00		

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Table B8. First stage OLS regressions for on- and off-farm fallow used in forest product equations

	Model 2		Model 4	
	Log of fallow area	Log of off-farm upstream fallow area – survey data	Log of fallow area	Log of off-farm upstream canopy cover – GIS data, 3km radius
Forest product price (village median)	-0.083	0.042*	-0.171***	0.014*
	[0.082]	[0.023]	[0.054]	[0.008]
Log of household size	-0.099	0.043	-0.092	-0.013
	[0.122]	[0.035]	[0.110]	[0.016]
Wage rate	-0.031	-0.021	-0.012	0.006
	[0.046]	[0.013]	[0.040]	[0.006]
Household head's schooling years	-0.003	0.007	-0.007	0.002
	[0.021]	[0.006]	[0.020]	[0.003]
Farm owner (binary)	0.116	-0.059	0.094	0.031*
	[0.130]	[0.037]	[0.117]	[0.017]
Car owner (binary)	-0.22	-0.114*	-0.241	-0.045
	[0.223]	[0.063]	[0.202]	[0.029]
Television owner (binary)	0.098	0.016	0.108	-0.03
	[0.145]	[0.041]	[0.132]	[0.019]
Use electricity (binary)	-0.092	-0.022	-0.053	0.017
	[0.145]	[0.041]	[0.135]	[0.020]
Own firewood stove (binary)	-0.218	-0.01	-0.151	0.046**
	[0.166]	[0.047]	[0.155]	[0.023]
Own gas stove (binary)	-0.08	-0.013	-0.068	-0.007
	[0.169]	[0.048]	[0.160]	[0.024]
Black clay soil (binary)	-0.27	-0.075	-0.289	-0.008
	[0.217]	[0.061]	[0.198]	[0.029]
Charcoal-enriched soil (binary)	0.025	-0.056	0.046	0.016
	[0.189]	[0.053]	[0.180]	[0.027]
Poor soil (binary)	0.082	0.006	-0.045	-0.032
	[0.276]	[0.078]	[0.245]	[0.036]
Slope	0.047*	0.014**	0.038*	0.010***
	[0.025]	[0.007]	[0.023]	[0.003]
No on-farm fallow (binary)	-1.995***	-0.004	-2.046***	-0.024
	[0.202]	[0.057]	[0.182]	[0.026]
No upstream fallow (binary)	0.748	-1.280***		
	[0.601]	[0.170]		
Log of farm size	0.818***	-0.033**	0.745***	0.017**
	[0.058]	[0.016]	[0.052]	[0.008]
Log of farm size –	-0.091	0.550***	-0.042	0.043***

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[34] The upstream neighborhood for each model corresponds to the respective upstream off-farm fallow definition: the neighborhood for Model 2 is all upstream households, while the neighborhood for Model 4 is upstream area within a 3km radius.

upstream weighted average[34]	[0.141]	[0.040]	[0.079]	[0.012]
Log of household size – upstream weighted average	0.129	0.027	-0.058	-0.014
	[0.422]	[0.119]	[0.087]	[0.013]
Wage rate – upstream weighted average	0.051	0.033	0.11	-0.092***
	[0.141]	[0.040]	[0.240]	[0.035]
Car owner (binary) – upstream weighted average	-0.069	-0.548**	-0.29	-0.107*
	[0.872]	[0.246]	[0.414]	[0.060]
Television owner (binary) – upstream weighted average	0.159	-0.205*	0.13	-0.021
	[0.386]	[0.109]	[0.230]	[0.034]
Own firewood stove – upstream weighted average	0.663	0.05	0.457	0.268***
	[0.613]	[0.173]	[0.314]	[0.046]
Own gas stove – upstream weighted average	-0.531	-0.339*	-0.353	0.059
	[0.612]	[0.173]	[0.252]	[0.037]
Black clay soil – upstream weighted average	-0.284	-1.127***	-0.085	-0.032
	[0.624]	[0.176]	[0.316]	[0.046]
Charcoal-enriched soil – upstream weighted average	-0.368	-0.223	-0.264	-0.049
	[0.592]	[0.167]	[0.283]	[0.041]
Poor soil – upstream weighted average	0.197	0.003	0.297	-0.125**
	[0.459]	[0.129]	[0.379]	[0.056]
Castanhal municipality	0.233	-0.210*	0.406*	-0.221***
	[0.387]	[0.109]	[0.227]	[0.033]
Igarapé Açu municipality	0.054	-0.277**	0.322	-0.107***
	[0.393]	[0.111]	[0.211]	[0.031]
Constant	0.304	1.594***	1.485	3.185***
	[1.393]	[0.393]	[0.957]	[0.139]
Observations	236	236	271	261
R-squared	0.74	0.9	0.74	0.72

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B9. Instrumental variables validity checks: p-values from including each instrument individually in the forest product probit and non-limit regression equations

	Model 2		Model 4	
	Probit	Non-limit regression	Probit	Nonlimit-regression
Log of farm size	0.31	0.75	0.33	0.96
Log of farm size – upstream weighted average[35]	0.14	0.25	0.16	0.86
Log of household size – upstream weighted average	0.15	0.28	0.53	0.69
Wage rate – upstream weighted average	0.96	0.32	0.87	0.47
Car owner – upstream weighted average	0.61	0.45	0.16	0.65
Television owner – upstream weighted average	0.88	0.29	0.46	0.32
Own firewood stove – upstream weighted average	0.73	0.62	0.44	0.76
Own gas stove – upstream weighted average	0.72	0.66	0.21	0.48
Black clay soil – upstream weighted average	0.24	0.89	0.61	0.98
Charcoal-enriched soil – upstream weighted average	0.62	0.60	0.49	0.87
Poor soil – upstream weighted average	0.72	0.51	0.16	0.50
Sargan test for overidentification		0.77		0.95
Amemiya-Lee-Newey test for overidentification	0.89		0.40	
Hausman Chi-2 test for joint exogeneity of on- and off-farm fallow		0.03		0.08
Wald test for joint exogeneity of on- and off-farm fallow	0.84		0.04	

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[35] The upstream neighborhood for each model corresponds to the upstream off-farm fallow definition: the neighborhood for Model 2 is all upstream households, while the neighborhood for Model 4 is upstream area within a 3km radius.

Table B10. Robustness analysis: forest product probit excluding observations from top and bottom 10 percentiles of on-farm fallow and upstream fallow area

	Full sample	Excluding farms with no on-farm fallow area	Excluding top 10% of on-farm fallow area	Excluding bottom 10% of upstream fallow	Excluding top 10% of upstream fallow area
Log on-farm fallow area	0.243*** [0.091]	0.239*** [0.091]	0.270*** [0.103]	0.251*** [0.095]	0.195* [0.101]
Log off-farm fallow – upstream survey fallow area	0.389* [0.226]	0.266 [0.239]	0.379 [0.235]	0.975** [0.477]	0.264 [0.269]
Forest product price (village median)	-0.169 [0.143]	-0.2 [0.167]	-0.122 [0.147]	-0.272 [0.175]	-0.173 [0.144]
Log household size	0.790*** [0.237]	0.749*** [0.251]	0.808*** [0.250]	0.848*** [0.254]	0.784*** [0.242]
Agricultural wage rate	-0.201** [0.081]	-0.202** [0.084]	-0.228*** [0.086]	-0.197** [0.084]	-0.204** [0.081]
Household head schooling years	0.036 [0.038]	0.033 [0.041]	0.055 [0.040]	0.052 [0.040]	0.039 [0.039]
Farm owner (binary)	0.233 [0.253]	0.399 [0.270]	0.413 [0.270]	0.374 [0.266]	0.251 [0.261]
Own car (binary)	-0.839** [0.359]	-0.735** [0.372]	-0.948** [0.375]	-0.898** [0.365]	-0.798** [0.361]
Own television (binary)	-0.002 [0.281]	-0.008 [0.304]	-0.142 [0.304]	-0.049 [0.308]	-0.05 [0.297]
Use electricity (binary)	-0.672** [0.291]	-0.640** [0.300]	-0.797** [0.314]	-0.687** [0.314]	-0.582* [0.310]
Own firewood stove (binary)	0.238 [0.283]	0.255 [0.307]	0.361 [0.295]	0.227 [0.304]	0.316 [0.293]
Own gas stove (binary)	-1.157*** [0.445]	-0.869* [0.461]	-1.148** [0.461]	-0.984** [0.454]	-1.185** [0.469]
Black clay soil (binary)	0.781* [0.441]	0.669 [0.461]	0.981** [0.465]	0.394 [0.476]	1.063** [0.493]
Charcoal-enriched soil (binary)	0.184 [0.340]	0.252 [0.355]	0.117 [0.345]	0.189 [0.368]	0.093 [0.348]
Poor soil (binary)	-0.325 [0.528]	0.102 [0.625]	-0.276 [0.537]	-0.281 [0.553]	-0.333 [0.529]
Slope	-0.009 [0.045]	-0.01 [0.047]	-0.006 [0.048]	-0.042 [0.053]	-0.017 [0.052]
Castanhal municipality (binary)	0.685** [0.345]	0.519 [0.380]	0.972*** [0.374]	0.889** [0.398]	0.834** [0.371]

Igarapé Açu municipality (binary)	1.313***	0.894**	1.391***	1.656***	1.430***
	[0.399]	[0.435]	[0.415]	[0.477]	[0.417]
No on-farm fallow area (binary)	0.249		0.386	0.417	0.089
	[0.437]		[0.452]	[0.465]	[0.467]
No upstream fallow area (binary)	-2.157*		-2.153*		-2.466**
	[1.125]		[1.168]		[1.204]
Constant	0.481	0.811	0.173	-1.294	0.81
	[1.300]	[1.372]	[1.344]	[1.806]	[1.343]
Observations	236	203	213	213	212
Pseudo R-squared	0.31	0.26	0.32	0.31	0.30
Log likelihood	-98.25	-86.23	-89.01	-85.81	-91.76

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B11. Robustness analysis: forest product probit excluding observations from top and bottom 10 percentiles of on-farm fallow and upstream canopy cover

	Full sample	Excluding farms with no on-farm fallow area	Excluding top 10% of on-farm fallow area	Excluding bottom 10% of upstream fallow	Excluding top 10% of upstream fallow area
Log on-farm fallow area	0.275***	0.277***	0.299***	0.275***	0.333***
	[0.089]	[0.094]	[0.101]	[0.089]	[0.129]
Log off-farm fallow – 3km upstream GIS canopy cover	1.086	-0.199	1.077	1.086	1.187
	[0.736]	[0.855]	[0.764]	[0.736]	[1.487]
Forest product price (village median)	0.107	-0.307*	0.123	0.107	0.350**
	[0.097]	[0.177]	[0.100]	[0.097]	[0.153]
Log household size	0.735***	0.792***	0.733***	0.735***	0.987***
	[0.214]	[0.241]	[0.223]	[0.214]	[0.307]
Agricultural wage rate	-0.182**	-0.167**	-0.203***	-0.182**	-0.039
	[0.072]	[0.076]	[0.075]	[0.072]	[0.115]
Household head schooling years	0.029	0.028	0.041	0.029	0.035
	[0.036]	[0.040]	[0.037]	[0.036]	[0.048]
Farm owner (binary)	0.009	0.389	0.119	0.009	0.17
	[0.222]	[0.257]	[0.231]	[0.222]	[0.317]
Own car (binary)	-0.748**	-0.869**	-0.838**	-0.748**	-0.728*
	[0.344]	[0.367]	[0.356]	[0.344]	[0.434]
Own television (binary)	0.052	-0.017	-0.064	0.052	-0.438
	[0.264]	[0.299]	[0.283]	[0.264]	[0.441]
Use electricity (binary)	-0.670**	-0.601**	-0.759***	-0.670**	0.146
	[0.266]	[0.294]	[0.284]	[0.266]	[0.414]
Own firewood stove (binary)	0.315	0.228	0.437	0.315	0.275
	[0.267]	[0.307]	[0.278]	[0.267]	[0.346]
Own gas stove (binary)	-0.959**	-1.052**	-0.927**	-0.959**	-0.821
	[0.383]	[0.460]	[0.394]	[0.383]	[0.560]
Black clay soil (binary)	0.548	0.738	0.696*	0.548	1.074
	[0.388]	[0.463]	[0.406]	[0.388]	[0.925]
Charcoal-enriched soil (binary)	0.076	0.304	0.042	0.076	-0.41
	[0.324]	[0.361]	[0.328]	[0.324]	[0.491]
Poor soil (binary)	-0.273	-0.242	-0.244	-0.273	-0.806
	[0.441]	[0.510]	[0.447]	[0.441]	[0.526]
Slope	-0.018	0.01	-0.016	-0.018	-0.048
	[0.042]	[0.046]	[0.044]	[0.042]	[0.089]
Castanhal municipality (binary)	0.755*	0.708	1.040**	0.755*	0.1
	[0.399]	[0.460]	[0.423]	[0.399]	[0.663]
Igarapé Açu municipality (binary)	0.849**	0.956**	0.948**	0.849**	0.626
	[0.354]	[0.426]	[0.372]	[0.354]	[0.720]
No on-farm fallow	0.072		0.174	0.072	0.23

area (binary)	[0.394]		[0.408]	[0.394]	[0.523]
Constant	-3.494	2.421	-3.651	-3.494	-6.601
	[2.499]	[3.093]	[2.570]	[2.499]	[4.833]
Observations	261	222	237	261	136
Pseudo R-squared	0.26	0.26	0.27	0.26	0.28
Log likelihood	-117.53	-92.94	-107.75	-117.53	-64.66

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B12. Robustness analysis: forest product non-limit regression excluding observations from top and bottom 10 percentiles of on-farm fallow and upstream fallow area

	Full sample	Excluding farms with no on-farm fallow area	Excluding top 10% of on-farm fallow area	Excluding bottom 10% of upstream fallow	Excluding top 10% of upstream fallow area
Log on-farm fallow area	0.043	0.058	-0.008	-0.052	0.056
	[0.125]	[0.127]	[0.156]	[0.126]	[0.138]
Log off-farm fallow – upstream survey fallow area	0.565*	0.506	0.637*	-0.644	0.601*
	[0.309]	[0.315]	[0.340]	[0.572]	[0.350]
Forest product price (village median)	0.063	0.111	0.071	0.057	0.108
	[0.210]	[0.215]	[0.227]	[0.218]	[0.226]
Log household size	0.153	0.098	0.184	0.338	0.121
	[0.296]	[0.314]	[0.326]	[0.305]	[0.318]
Agricultural wage rate	0.002	-0.015	0.024	0.006	0.026
	[0.113]	[0.115]	[0.125]	[0.113]	[0.119]
Household head schooling years	0.026	0.024	0.007	-0.014	0.025
	[0.052]	[0.054]	[0.058]	[0.053]	[0.057]
Farm owner (binary)	-0.24	-0.23	-0.325	-0.366	-0.454
	[0.297]	[0.315]	[0.333]	[0.297]	[0.333]
Own car (binary)	1.288**	1.314**	1.512**	1.282**	1.273**
	[0.577]	[0.586]	[0.616]	[0.567]	[0.598]
Own television (binary)	0.585*	0.643**	0.437	0.496	0.588*
	[0.304]	[0.323]	[0.349]	[0.308]	[0.329]
Use electricity (binary)	-1.025***	-1.197***	-1.139***	-0.890***	-0.962***
	[0.293]	[0.309]	[0.330]	[0.297]	[0.322]
Own firewood stove (binary)	0.325	0.107	0.228	-0.038	0.301
	[0.441]	[0.474]	[0.494]	[0.457]	[0.497]
Own gas stove (binary)	-0.026	-0.229	0.156	0.085	-0.123
	[0.336]	[0.356]	[0.383]	[0.340]	[0.379]
Black clay soil (binary)	0.958**	1.075**	0.749	1.083**	0.742
	[0.446]	[0.461]	[0.521]	[0.457]	[0.533]
Charcoal-enriched soil (binary)	-0.218	-0.28	-0.075	0.239	-0.344
	[0.431]	[0.437]	[0.468]	[0.455]	[0.461]
Poor soil (binary)	0.462	0.811	0.566	0.37	0.374
	[0.582]	[0.629]	[0.612]	[0.584]	[0.612]
Slope	-0.063	-0.074	-0.047	0.015	-0.093
	[0.052]	[0.054]	[0.059]	[0.059]	[0.079]
Castanhal municipality (binary)	0.676	0.741	0.57	0.291	0.555
	[0.495]	[0.505]	[0.543]	[0.531]	[0.559]
Igarapé Açu municipality (binary)	0.299	0.07	0.245	-0.186	0.198
	[0.510]	[0.522]	[0.567]	[0.574]	[0.586]

No on-farm fallow	-0.267	0	-0.381	-0.578	-0.447
area (binary)	[0.639]	[0.000]	[0.704]	[0.636]	[0.691]
No upstream fallow	0.424	0.17	0.883	0	0.468
area (binary)	[1.792]	[1.817]	[1.904]	[0.000]	[1.910]
Constant	2.622	3.229*	2.448	6.796***	2.557
	[1.785]	[1.849]	[1.970]	[2.306]	[1.901]
Observations	161	146	141	150	143
R-squared	0.18	0.2	0.18	0.18	0.18

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B13. Robustness analysis: forest product non-limit regression excluding observations from top and bottom 10 percentiles of on-farm fallow and upstream canopy cover

	Full sample	Excluding farms with no on-farm fallow area	Excluding top 10% of on-farm fallow area	Excluding bottom 10% of upstream fallow	Excluding top 10% of upstream fallow area
Log on-farm fallow area	0.023	0.045	-0.036	0.023	0.025
	[0.119]	[0.122]	[0.151]	[0.119]	[0.230]
Log off-farm fallow – 3km upstream GIS canopy cover	0.947	0.843	1.153	0.947	-1.934
	[0.875]	[0.953]	[0.952]	[0.875]	[2.106]
Forest product price (village median)	0.156	0.244	0.162	0.156	0.085
	[0.184]	[0.230]	[0.197]	[0.184]	[0.327]
Log household size	0.226	0.188	0.243	0.226	0.415
	[0.276]	[0.297]	[0.302]	[0.276]	[0.519]
Agricultural wage rate	-0.029	-0.028	-0.006	-0.029	-0.053
	[0.094]	[0.097]	[0.102]	[0.094]	[0.144]
Household head schooling years	0.074	0.079	0.061	0.074	0.062
	[0.048]	[0.051]	[0.053]	[0.048]	[0.086]
Farm owner (binary)	-0.328	-0.314	-0.375	-0.328	-0.765
	[0.287]	[0.307]	[0.324]	[0.287]	[0.531]
Own car (binary)	1.112**	1.086*	1.292**	1.112**	1.516**
	[0.542]	[0.556]	[0.574]	[0.542]	[0.738]
Own television (binary)	0.692**	0.719**	0.611*	0.692**	0.376
	[0.289]	[0.311]	[0.332]	[0.289]	[0.512]
Use electricity (binary)	-1.024***	-1.177***	-1.119***	-1.024***	-1.042*
	[0.282]	[0.303]	[0.317]	[0.282]	[0.539]
Own firewood stove (binary)	0.317	0.164	0.279	0.317	0.693
	[0.416]	[0.459]	[0.461]	[0.416]	[0.635]
Own gas stove (binary)	0.102	-0.061	0.261	0.102	0.634
	[0.321]	[0.343]	[0.362]	[0.321]	[0.680]
Black clay soil (binary)	0.746*	0.871*	0.515	0.746*	-0.679
	[0.423]	[0.443]	[0.490]	[0.423]	[1.309]
Charcoal-enriched soil (binary)	-0.447	-0.506	-0.364	-0.447	-0.14
	[0.417]	[0.429]	[0.452]	[0.417]	[0.898]
Poor soil (binary)	0.625	0.976	0.748	0.625	0.01
	[0.549]	[0.596]	[0.579]	[0.549]	[0.762]
Slope	-0.074	-0.08	-0.064	-0.074	-0.175
	[0.049]	[0.052]	[0.055]	[0.049]	[0.131]
Castanhal municipality (binary)	0.665	0.666	0.615	0.665	0.614
	[0.517]	[0.549]	[0.578]	[0.517]	[1.143]
Igarapé Açu municipality (binary)	-0.066	-0.291	-0.139	-0.066	0.483
	[0.431]	[0.474]	[0.489]	[0.431]	[1.118]

No on-farm fallow area	-0.094	0	-0.193	-0.094	-0.838
(binary)	[0.592]	[0.000]	[0.657]	[0.592]	[0.965]
Constant	0.722	1.02	-0.013	0.722	10.231
	[3.205]	[3.653]	[3.460]	[3.205]	[7.143]
Observations	184	166	163	184	85
R-squared	0.17	0.18	0.16	0.17	0.28

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Figure B5. On-farm fallow elasticity in forest product harvests and 95% confidence interval, excluding one observation at a time (Model 1)

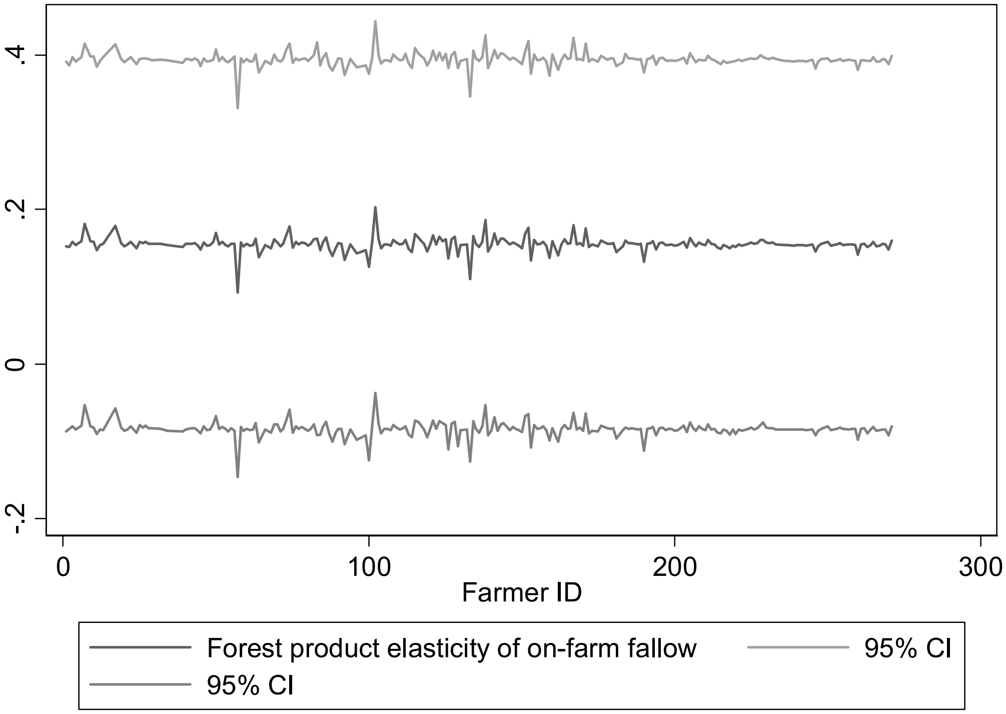

Figure B6. Upstream fallow elasticity in forest product harvests and 95% confidence interval, excluding one observation at a time (Model 1)

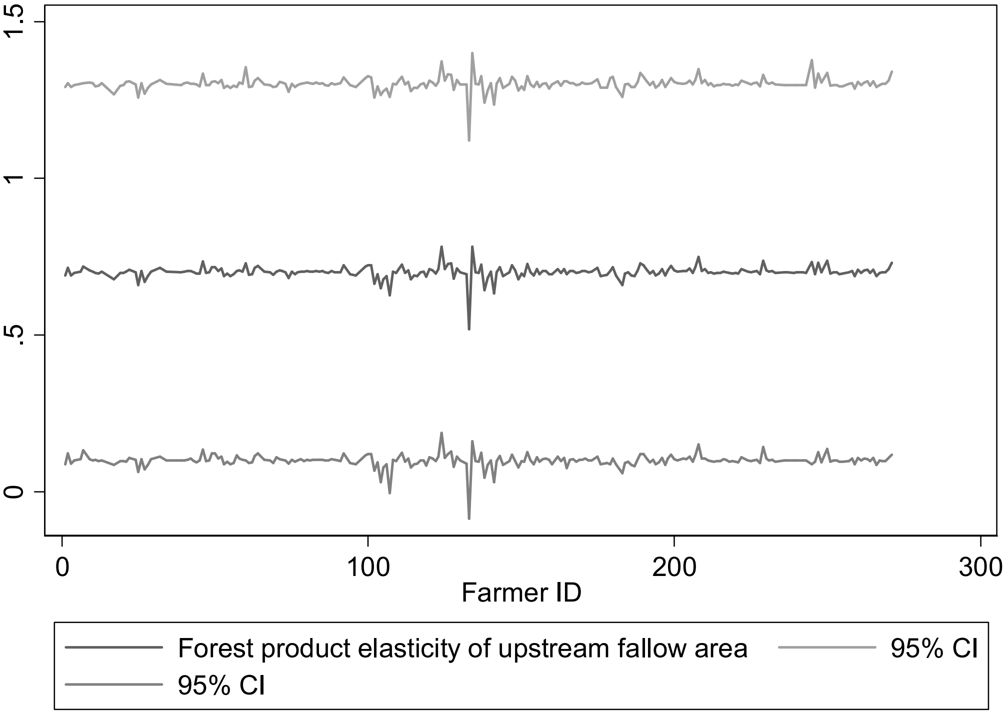

Figure B7. On-farm fallow elasticity in forest product harvests and 95% confidence interval, excluding one observation at a time (Model 3)

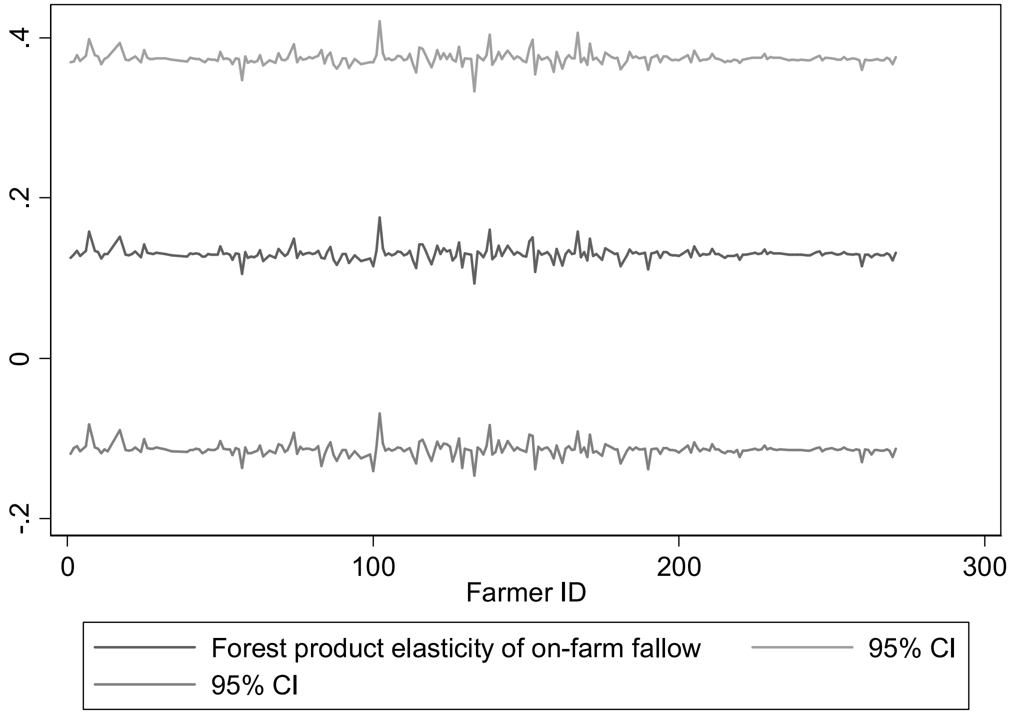

Figure B8. Upstream fallow elasticity in forest product harvests and 95% confidence interval, excluding one observation at a time (Model 3)

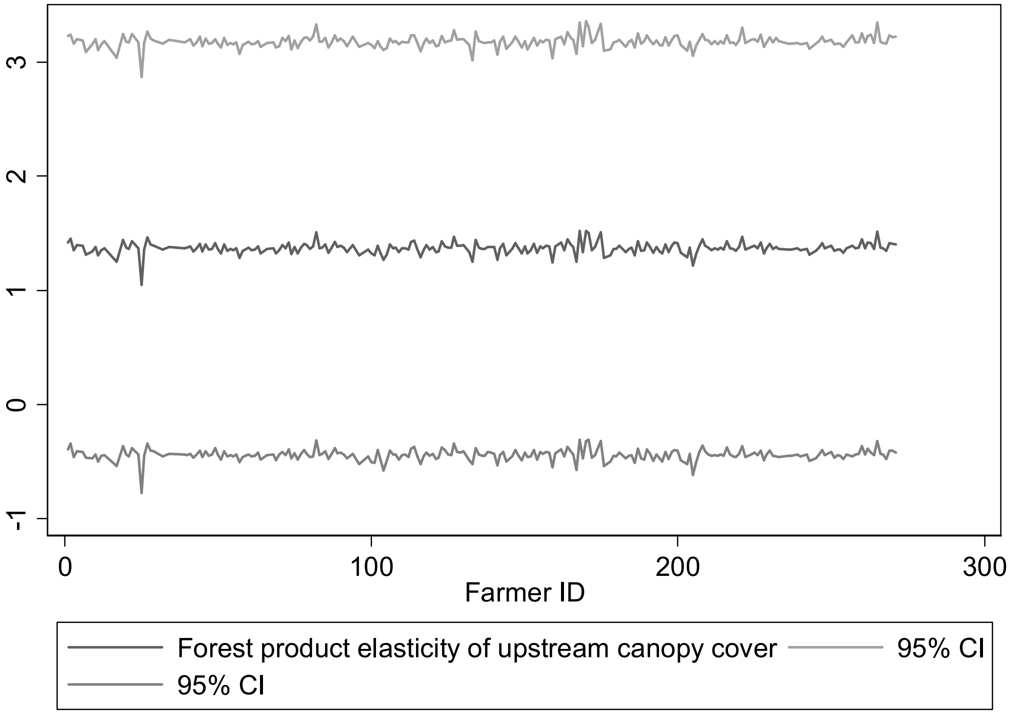

Table B14. Forest product harvesting: probit equation including downstream forest fallow

	SEM probit (1)	SEM-IV Probit (2)	SEM probit (3)	SEM-IV probit (4)
Log on-farm fallow area	0.299***	0.304**	0.315***	0.422***
	[0.123]	[.152]	[0.104]	[0.153]
Log off-farm fallow – upstream survey fallow area	0.496**	1.487		
	[0.263]	[1.888]		
Log off-farm fallow – 3 km upstream GIS canopy cover	-0.281	-1.373		
	[0.302]	[1.547]		
Log off-farm fallow – downstream survey fallow area			1.323	1.728
			[1.048]	[1.780]
Log off-farm fallow – 3 km downstream GIS canopy cover			-0.024	-0.380
			[0.915]	[1.499]
Forest product price (village median)	-0.276*	-0.233*	0.103	0.113
	0.180]	[0.167]	[0.110]	[0.117]
Log household size	0.964***	1.014***	0.882***	0.906***
	[0.269]	[0.266]	[0.263]	[0.242]
Agricultural wage rate	-0.238***	-0.246***	-0.210***	-0.201**
	[0.098]	[0.095]	[0.084]	[0.079]
Household head schooling years	0.053	0.060*	0.027	-0.028
	[0.046]	[0.043]	[0.242]	[0.246]
Farm owner (binary)	0.297	0.238	0.041	0.050
	[0.308]	[0.295]	[0.042]	[0.041]
Own car (binary)	-0.980**	-0.986***	-0.859***	-0.822**
	[0.426]	[0.411]	[0.381]	[0.387]
Own television (binary)	-0.037	0.091	0.058	0.069
	[0.314]	[0.323]	[0.297]	[0.317]
Use electricity (binary)	-0.799**	-0.846***	-0.816***	-0.748***
	[0.344]	[0.343]	[0.334]	[0.313]
Own firewood stove (binary)	0.266	0.338	0.381	0.403*
	[0.319]	[0.328]	[0.296]	[0.317]
Own gas stove (binary)	-1.411***	-1.504***	-1.118***	-1.186***
	[0.484]	[0.548]	[0.475]	[0.428]
Black clay soil (binary)	0.792*	0.631*	0.614*	0.516
	[0.551]	[0.495]	[0.452]	[0.461]
Charcoal-enriched soil (binary)	0.150	0.114	0.060	0.121
	[0.397]	[0.385]	[0.391]	[0.376]
Poor soil (binary)	-0.475	-0.439	-0.293	-0.339
	[0.587]	[0.610]	[0.524]	[0.506]
Slope	-0.027	-0.033	-0.019	-0.036
	[0.048]	[0.053]	[0.049]	[0.054]
Castanhal municipality (binary)	0.660*	0.837*	0.888**	0.848*
	[0.419]	[0.569]	[0.480]	[0.545]
Igarapé Açu municipality (binary)	1.420***	1.310***	0.954**	0.899**
	[0.474]	[0.464]	[0.438]	[0.441]

No on-farm fallow area (binary)	0.211	0.541	0.082	0.445
	[0.545]	[0.596]	[0.428]	0.503]
No upstream fallow area (binary)	-2.540**	-4.281***		
	[1.297]	[1.282]		
Constant	1.800	1.784	-4.152	-4.692
	[1.758[	[5.023]	[3.353]	[4.238]
Spatial error correlation coefficient	0.548***	0.545***	0.511***	0.502***
(λ)	[0.264]	[0.248]	[0.253]	[0.265]
Observations	236	236	261	261
McFadden R-squared	0.30	0.29	0.25	0.25

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Table B15. Forest product harvesting: conditional outcome equation including downstream forest fallow

	SEM (1)	SEM-IV (2)	SEM (3)	SEM-IV (4)
Log on-farm fallow area	0.066	0.257*	0.018	0.132
	[0.107]	[0.144]	[0.113]	[0.150]
Log off-farm fallow – upstream survey fallow area	0.546*	1.63		
	[0.281]	[1.632]		
Log off-farm fallow – 3 km upstream GIS canopy cover			0.586	-1.568
			[0.982]	[1.901]
Log off-farm fallow – downstream survey fallow area	-0.015	-1.257		
	[0.175]	[1.686]		
Log off-farm fallow – 3 km downstream GIS canopy cover			0.68	3.161*
			[1.099]	[2.221]
Forest product price (village median)	0.035	0.15	0.157	0.181
	[0.188]	[0.188]	[0.175]	[0.175]
Log household size	0.088	0.239	0.198	0.312
	[0.265]	[0.271]	[0.264]	[0.272]
Agricultural wage rate	0.027	-0.009	-0.026	-0.049
	[0.100]	[0.101]	[0.088]	[0.088]
Household head schooling years	0.03	0.057	0.069	0.080*
	[0.047]	[0.047]	[0.046]	[0.046]
Farm owner (binary)	-0.188	-0.146	-0.339	-0.34
	[0.269]	[0.274]	[0.272]	[0.282]
Own car (binary)	1.213**	1.206**	1.077**	1.250**
	[0.525]	[0.530]	[0.513]	[0.521]
Own television (binary)	0.626**	0.726***	0.691**	0.743***
	[0.280]	[0.276]	[0.272]	[0.273]
Use electricity (binary)	-1.074***	-1.111***	-1.024***	-1.012***
	[0.274]	[0.277]	[0.267]	[0.266]
Own firewood stove (binary)	0.409	0.397	0.299	0.255
	[0.380]	[0.395]	[0.392]	[0.423]
Own gas stove (binary)	-0.018	-0.171	0.123	0.071
	[0.308]	[0.309]	[0.306]	[0.310]
Black clay soil (binary)	0.957**	0.709*	0.815**	0.7
	[0.417]	[0.421]	[0.413]	[0.431]
Charcoal-enriched soil (binary)	-0.128	-0.254	-0.414	-0.518
	[0.388]	[0.392]	[0.396]	[0.401]
Poor soil (binary)	0.432	0.505	0.67	0.631
	[0.545]	[0.557]	[0.527]	[0.561]
Slope	-0.063	-0.065	-0.074	-0.106**
	[0.048]	[0.049]	[0.047]	[0.052]
Castanhal municipality (binary)	0.643	0.526	0.727	0.898
	[0.444]	[0.519]	[0.500]	[0.702]
Igarapé Açu municipality (binary)	0.227	-0.27	-0.033	-0.044
	[0.471]	[0.433]	[0.411]	[0.432]

No on-farm fallow area (binary)	-0.178	0.668	-0.135	0.329
	[0.563]	[0.634]	[0.563]	[0.639]
No upstream fallow area (binary)	0.408	-1.287		
	[1.635]	[1.462]		
Constant	3.01	2.537	-0.391	-1.879
	[2.066]	[4.204]	[3.812]	[7.424]
Spatial error correlation coefficient (λ)	0.153	0.198	0.053	0.037
	[0.185]	[0.196]	[0.218]	[0.275]
Observations	167	167	184	184
R-squared	0.19	0.19	0.17	0.19
Log likelihood	-293.22	-292.77	-330.89	-329.30

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Appendix C

Table C1. First stage equations for upstream forest fallow used in 2SLS spatial model of percent area under fallow

	Upstream survey fallow area	3km upstream GIS canopy cover
Forest product price	0.018	-0.005
	[0.033]	[0.022]
Annual crop village price index	10.861	-56.354
	[13.639]	[49.276]
Perennial crop village price index	-0.278	-1.444
	[0.540]	[2.809]
Fertilizer crop village price index	-8.193	-8.858
	[7.780]	[6.585]
Transportation cost	371.907*	139.316
	[204.822]	[138.193]
Transportation frequency	0.301	4.901
	[0.712]	[3.390]
Wage rate	-0.105	0.043
	[0.335]	[0.153]
Log of household size	1.132	-0.213
	[0.892]	[0.429]
Log of farm size	-0.666	0.215
	[0.428]	[0.196]
Farm owner (binary)	0.193	0.633
	[0.943]	[0.440]
Household head schooling years	0.018	0.073
	[0.158]	[0.074]
Own firewood stove (binary)	-2.445**	1.273**
	[1.195]	[0.570]
Own gas stove (binary)	0.063	-0.783
	[1.299]	[0.609]
Own car (binary)	-2.944*	-1.748**
	[1.593]	[0.748]
Own television (binary)	0.321	-0.546
	[1.071]	[0.500]
Use electricity (binary)	-1.255	-0.222
	[1.128]	[0.580]
Poor soil (binary)	-1.097	-0.1
	[1.991]	[0.923]
Charcoal-enriched soil (binary)	0.355	0.488
	[1.397]	[0.689]
Black clay soil (binary)	-0.923	0.933
	[1.685]	[0.810]
Slope	0.159	0.126
	[0.274]	[0.128]

Forest product price– upstream weighted average[36]	0.011	0.071**
	[0.217]	[0.028]
Annual crop price index – upstream weighted average	-14.026	60.25
	[13.872]	[49.236]
Perennial crop price index – upstream weighted average	4.341***	0.415
	[1.026]	[2.838]
Fertilizer – upstream weighted average	-42.191**	-0.427
	[19.449]	[8.225]
Transportation cost – upstream weighted average	314.884	315.621**
	[284.011]	[152.636]
Transportation frequency – upstream weighted average	-7.552***	-4.396
	[1.428]	[3.467]
Wage rate – upstream weighted average	3.959***	-1.115***
	[1.200]	[0.361]
Log of household size – upstream weighted average	3.555	-3.574***
	[4.202]	[1.007]
Log of farm size – upstream weighted average	10.372***	0.929***
	[1.053]	[0.332]
Farm owner – upstream weighted average	22.829***	4.333***
	[4.203]	[1.122]
Household head schooling years – upstream weighted average	1.006	2.570***
	[0.661]	[0.624]
Own firewood stove – upstream weighted average	-15.347***	7.459***
	[4.930]	[1.262]
Own gas stove – upstream weighted average	-0.385	0.726
	[5.116]	[1.110]
Own car – upstream weighted average	-39.419***	-5.692***
	[7.745]	[1.674]
Own television – upstream weighted average	17.075***	-1.045
	[3.775]	[1.048]
Use electricity – upstream weighted average	-9.638***	-1.632*
	[3.349]	[0.977]
Poor soil (binary) – upstream weighted average	-36.206***	-0.827
	[7.791]	[1.237]
Charcoal-enriched soil (binary) – upstream weighted average	1.535	4.161**
	[6.487]	[2.110]
Black clay soil (binary) – upstream weighted average	-9.945*	2.258
	[5.164]	[1.551]
Slope – upstream weighted average	0.348	-0.279
	[0.552]	[0.185]
Castanhal municipality (binary)	-23.826***	1.244
	[4.534]	[1.467]

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[36] The upstream neighborhood for each model corresponds to the upstream off-farm fallow definition: the neighborhood for Model 2 is all upstream households, while the neighborhood for Model 4 is upstream area within a 3km radius.

Igarapé Açu municipality (binary)	-9.963*	-1.641
	[5.124]	[1.364]
Constant	15.235	30.434***
	[27.734]	[5.993]
Observations	236	261
R-squared	0.81	0.82

Standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

Appendix D

Table D1. Land clearing labor regression

	Land clearing labor
Cultivated area	3.568***
	[0.882]
Cultivated area squared	-0.079***
	[0.021]
On-farm fallow	0.292***
	[0.073]
Constant	12.420***
	[3.405]
Observations	271
R-squared	0.14

Standard errors in brackets
* significant at 10%; ** significant at 5%; *** significant at 1%

Table D2.Fallow management indicators assuming 6% interest rate

	(1)	(2)	(3)	(4)	Observations
Net elasticity of cultivated land	0.06	-0.07	0.12*	-0.09	233
	(0.29)	(0.35)	(0.28)	(0.37)	
Over-fallow (1 = yes, 0 = no)	0.29	0.12	0.42	0.13	269
Under-fallow (1 = yes, 0 = no)	0.03	0.05	0.03	0.04	269
Optimal fallow (1 = yes, 0 = no)	0.68	0.83	0.55	0.84	269

Table D3. Fallow management indicators assuming 20% interest rate

	(1)	(2)	(3)	(4)	Observations
Net elasticity of cultivated land	0.09*	-0.01	0.15**	-0.03	233
	(0.28)	(0.33)	(0.26)	(0.34)	
Over-fallow (1 = yes, 0 = no)	0.44	0.31	0.50	0.33	269
Under-fallow (1 = yes, 0 = no)	0.04	0.06	0.03	0.05	269
Optimal fallow (1 = yes, 0 = no)	0.52	0.63	0.46	0.62	269

Figure D1. Net elasticity of cultivated land distribution: Model 1

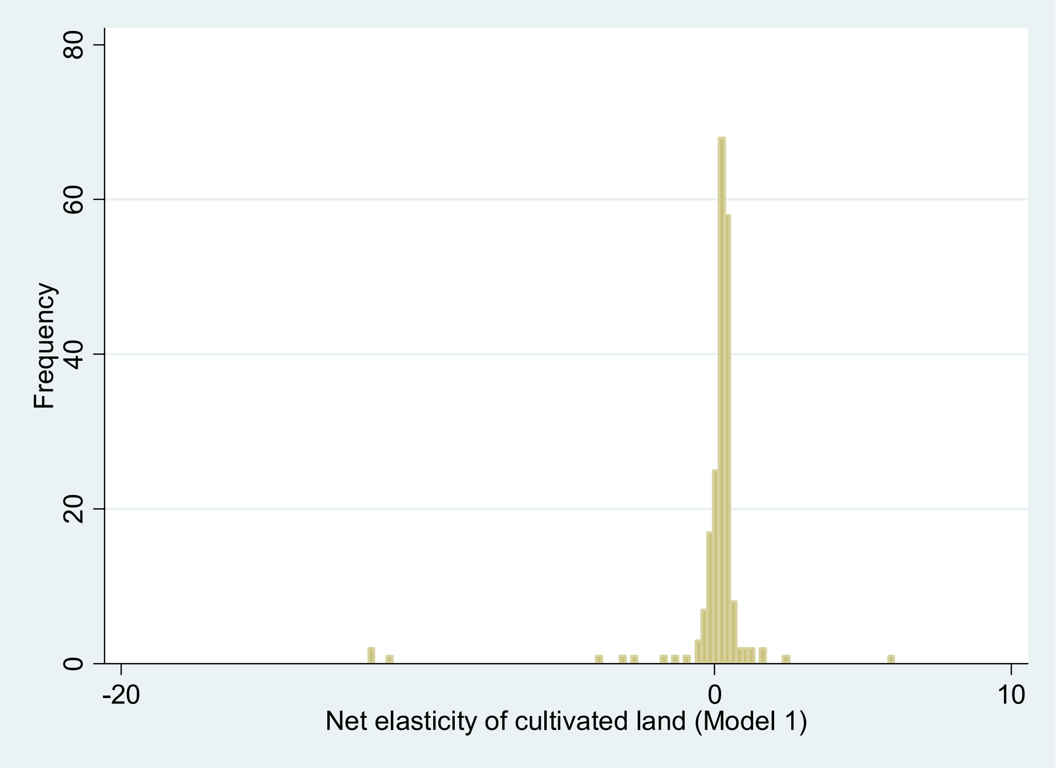


Figure D2. Net elasticity of cultivated land distribution: Model 2

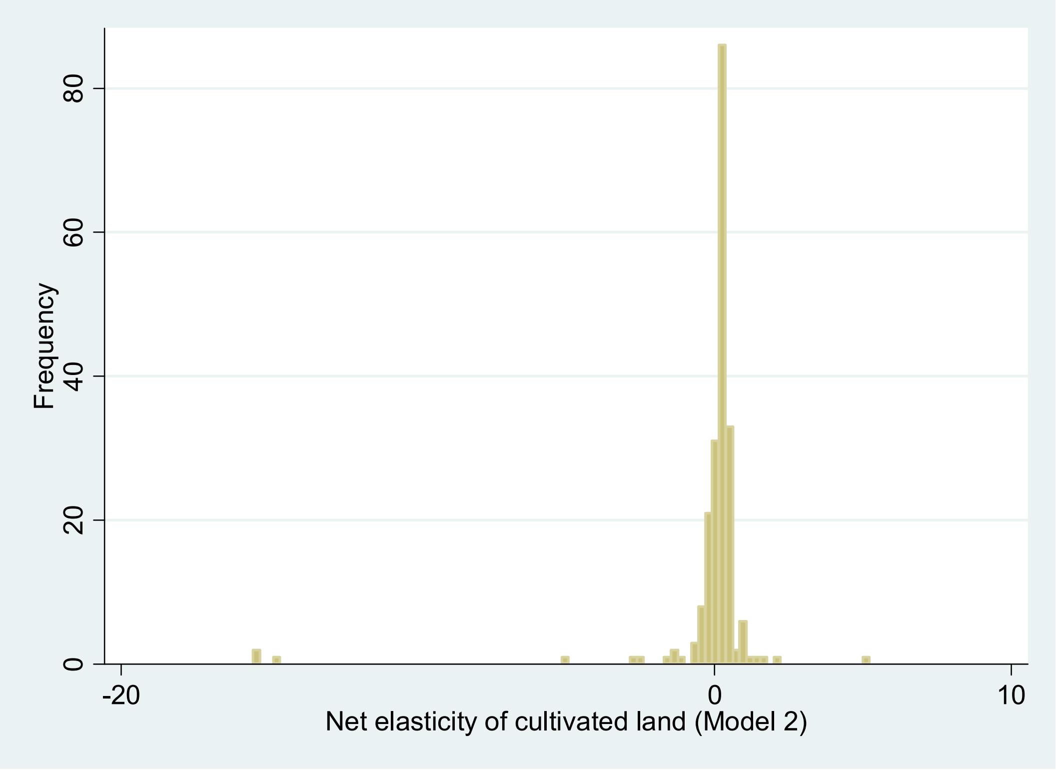


Figure D3. Net elasticity of cultivated land distribution: Model 3

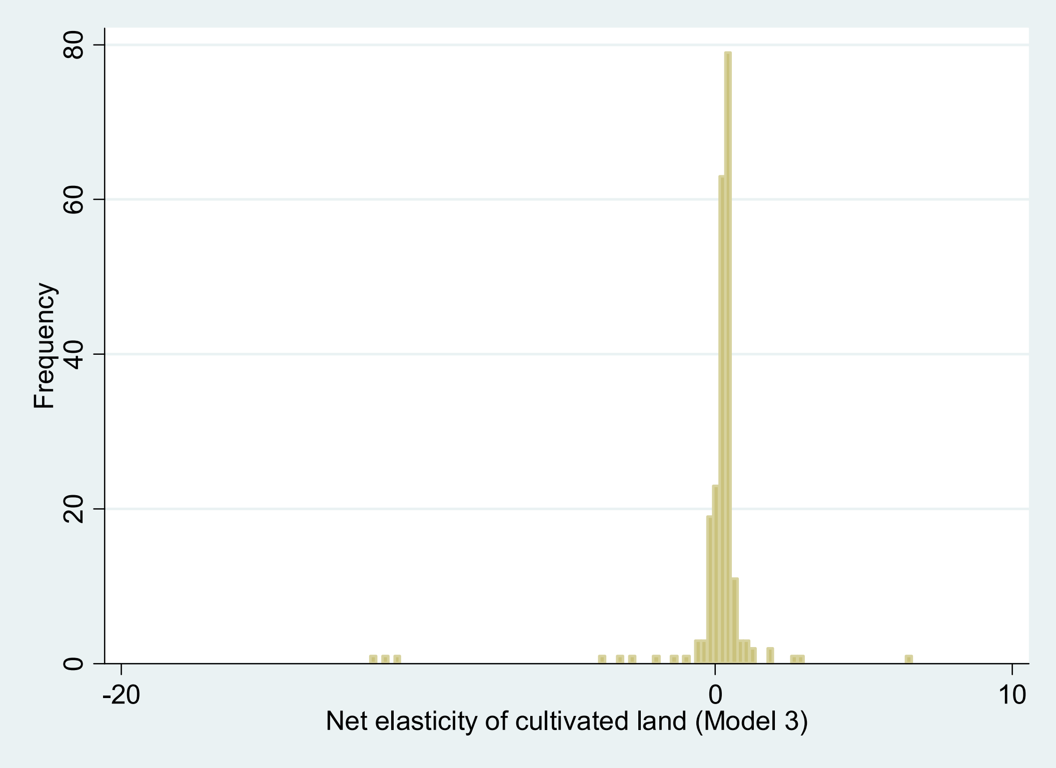
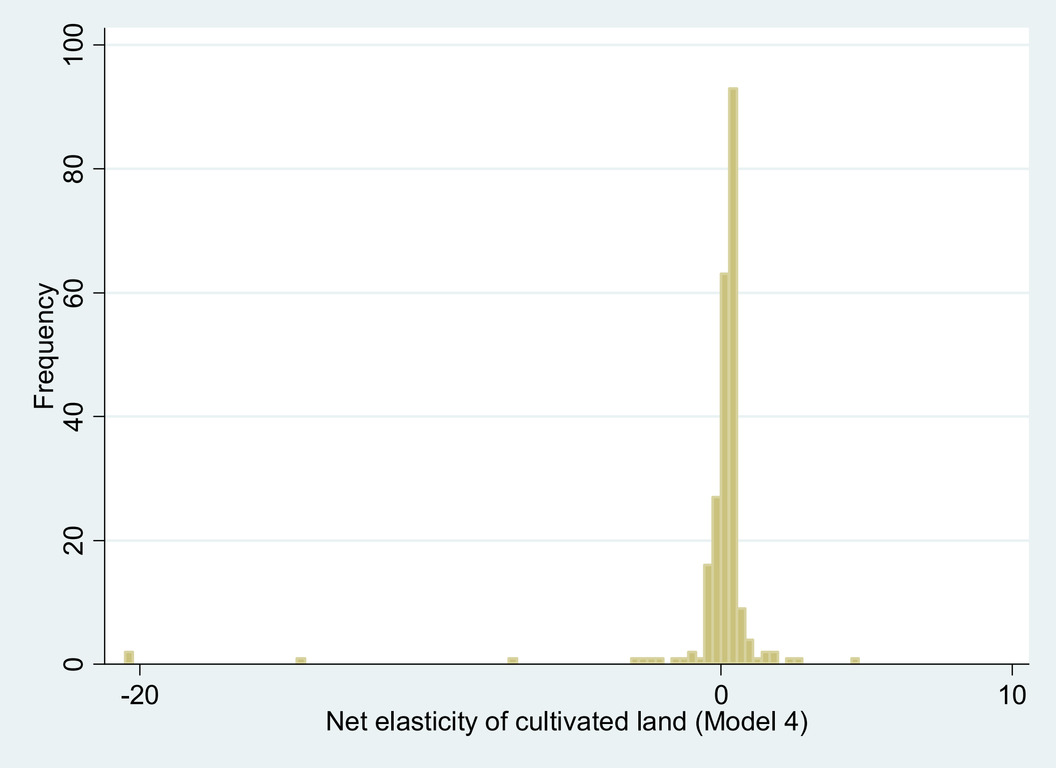


Figure D4. Net elasticity of cultivated land distribution: Model 4



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