DETERMINANTS OF LAND USE IN AMAZÔNIA: A FINE-SCALE SPATIAL ANALYSIS

KENNETH M. CHOMITZ AND TIMOTHY S. THOMAS

Wetter areas of the Amazon basin exhibit lower rates of agricultural conversion. Previous analyses, using relatively aggregate data on land cover, have been unable to determine the extent to which this reflects limited access versus unfavorable agroclimatic conditions. This article uses census-tract level data for the Brazilian Amazon to relate forest conversion and pasture productivity to precipitation, soil quality, infrastructure and market access, proximity to past conversion, and protection status. The probability that land is used for agriculture or intensively stocked with cattle declines markedly with increasing rainfall, other things equal.

Key words: Amazon, Brazil, deforestation, econometrics, land use, precipitation.

Is Western Amazônia suitable for agricultural development? If so, there could be difficult trade-offs between regional development and local and global environmental values, since this huge region's forests represent an immense store of carbon and of biodiversity, and play a role in local climate regulation (Laurance and Williamson). However, Schneider et al. and Sombroek argue that high levels of rainfall make this region intrinsically unattractive for annual crops and pasture. Sombroek asserts that where rainfall is high and dry seasons short, cattle are susceptible to parasites and insect pests; forest burning is incomplete, complicating the establishment of crops or pasture; crops such as rice, maize, and beans are subject to rotting; yields are depressed by light-limiting cloud cover; mechanization is difficult; and rural access roads are difficult to build and maintain.

Deforestation rates are, in fact, much lower in humid Western Amazônia than in the drier areas on the eastern and southern edges of the Amazon Basin. This is consistent with the hypothesis that rainfall deters agriculture. But an alternative hypothesis is that low deforestation rates in very humid areas simply reflect historical lack of accessibility. Roads have come recently, or not at all, to much of this region.

To choose between these hypotheses, therefore, we need to disentangle the effects of soils, climate, and markets on deforestation rates and agricultural outcomes. This article examines the determinants of land use and agricultural productivity through multivariate analysis of spatial data, improving on Pfaff's pioneering multivariate analysis in a number of significant ways. Most importantly, we include data on rainfall, together with more detailed measures of soil quality. Also, the census-tract-level data used here permit geographical resolution about twenty times finer than afforded by the *município*-level data used in Pfaff's study, and provide land use information not available with the remote sensing data used by Pfaff. Finally, our study area encompasses *cerrado* regions of the Legal Amazon, which necessarily were excluded from Pfaff's study, since remote sensing data cannot distinguish *cerrado* from deforestation. However, *cerrado* is drier and more accessible than moist forest, has suffered greater conversion, and arguably encompasses rarer and more threatened forms of biodiversity.

The results of this analysis must be interpreted with caution. The historical data used here cannot tell us what development patterns might be possible in the future using

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hypothetical new agricultural technologies. However, a record of the actual behavior of hundreds of thousands of farmers across the wide and varied landscape of Amazônia does provide insight into the geographical opportunities and constraints to agriculture as modulated by current technical and institutional conditions.

The article begins by presenting the data used for subsequent analyses. These data are used to provide a descriptive overview of land use in the Brazilian Amazon. An analytical section draws on these data to conduct two multivariate analyses: the determinants of agricultural land use, and the determinants of stocking rates of pasture. A concluding section summarizes findings and discusses their implications.

Data

Census Data on Land Use, Labor, and Cattle

We are grateful to the *Instituto Brasileiro de Geografia e Estatística* (IBGE) for providing us with tabulations of land use, labor, and cattle at the level of the census tract (*setor*), along with census tract boundary maps with scales of 1:50,000 to 1:250,000. We merged very small census tracts (less than 400 hectares) with adjacent ones, yielding 6,776 units of analysis.

We use the term "agricultural land" to describe land within agricultural establishments that falls in the following categories: productive land in crops, natural and planted pasture,[1] plantation forest, fallow, and "productive and unutilized." We use the ratio of agricultural land to nonwater census tract area as a measure of deforestation. Some caveats apply, since the Census categories were not designed for this purpose. In some cases the computed ratio was greater than one. This may reflect establishments that straddle a census tract border, but whose total area is recorded (according to standard Census procedure) in just one census tract. It may also reflect inaccurate estimates of area, overlapping land claims, or registration error in computing areas. Our measure of deforestation may underestimate historical deforestation for several reasons. It is possible that some long-abandoned parts of current establishments may now be in advanced regeneration and may be classified as natural forest. Also, it is possible that some establishments may have been entirely abandoned and not included in the Census.[2] Our deforestation estimates will exclude degraded land in any such areas, and will also exclude areas outside current establishments that have lost forest cover solely because of fires or logging (i.e., without follow-on conversion to agriculture). It also excludes "cryptic" deforestation—that is, thinning of trees through logging or fire that does not result in overt loss of forest cover (Nepstad et al.). Despite these limitations, these data are complementary to remote sensing measures of deforestation, which have their own strengths and drawbacks. Data derived from remote sensing are limited in their ability to distinguish different kinds of land use, are unavailable for areas with persistent cloud cover, and are not able to determine levels of deforestation in *cerrado* (savanna) areas, which make up a large portion of Amazônian land in agriculture.

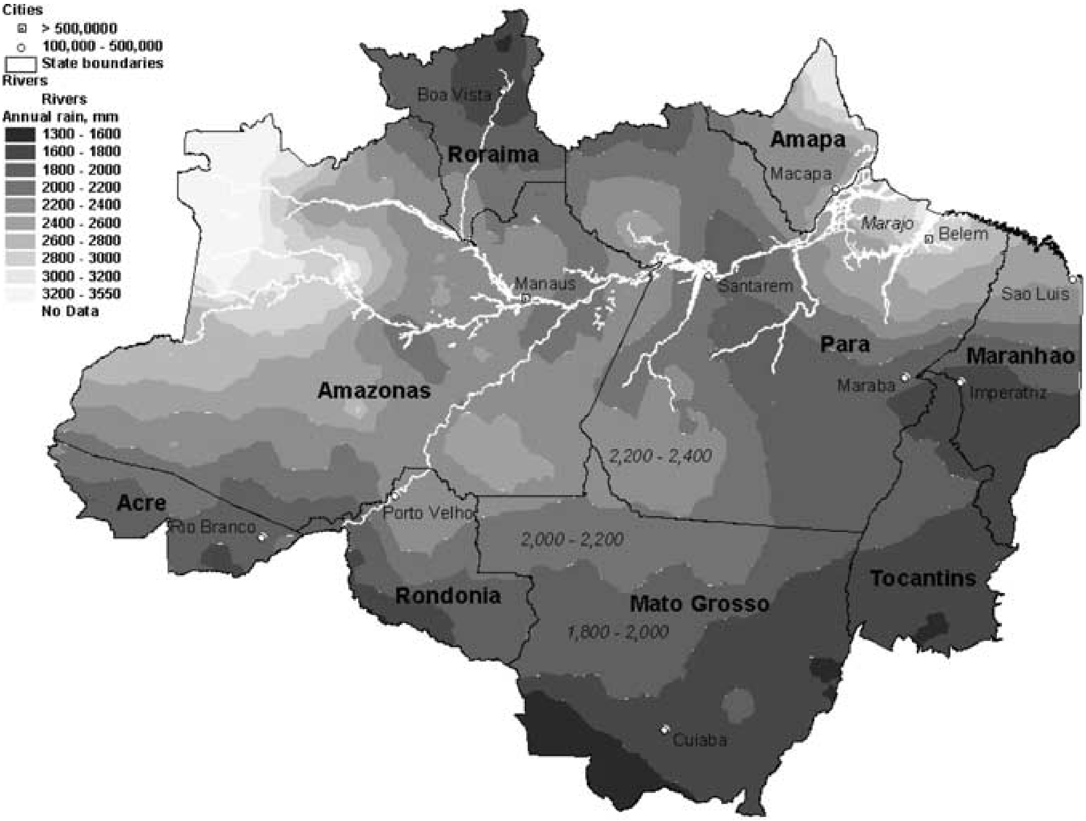
Explanatory Variables

Climate. We use monthly precipitation data for 1970–96 kindly provided by the CAMREX project, University of Washington. Each composite month is the mean of individual months formed by interpolations of gauge records of the *Agência Nacional de Energia Elétrica* to 0.05 degrees spatial resolution. Map 1 shows the mean annual precipitation based on these data. There is a strong gradient from high precipitation in northwest toward lower precipitation in the southeast, with an additional rainfall peak in the northeast. The number of dry months (the statistic stressed by Sombroek as a key limiting factor) is highly correlated with mean annual precipitation. Because the precipitation data extend only to 45° W, parts of the subsequent analysis exclude the easternmost portion of the Legal Amazon (part of Maranhão comprising about 1.3% of the land area of the Legal Amazon).

Soils. Data on soils were provided by Soil Survey Division of World Soil Resources of the U.S. Department of Agriculture (Eswaran and Reich). It summarizes the soils by their

[1] Based on our reading of the Census interviewers' guide and discussions with IBGE staff, we assume that *cerrado* (savannah, with varying degrees of tree cover) is classified as forest unless it is currently being used for grazing or agriculture, or was so used and had been abandoned recently. A *cerrado* area used for grazing is assumed to be classified as "natural pasture," an agricultural land use. We are not sure how Census interviewers classified natural grasslands that are not used for grazing (if such areas exist).

[2] There was a substantial decline between the last two Censuses in the area of establishments in Amazônas and in Acre.



Map 1. Rainfall, rivers, and cities of the legal Amazon

primary limiting factor. In our study area, the 1:5,000,000 scale data distinguish thirteen soil categories, though worldwide their system notes about twice that many.

Vegetation. IMAZON (2000a) used the Brazilian Vegetation Map (*Ministerio da Agricultura* and IBGE), which describes the natural vegetative cover for all of Brazil at 1 : 5,000,000 scale, and reclassifies the many vegetation types into six groups. While natural vegetation may itself reflect soil and climatic characteristics, these six vegetation groups may provide additional biogeophysical and economic information related to the ease and attractiveness of converting the land to agricultural use. For instance, *cerrado* will have lower costs of clearing, but also lower revenues from sale of timber, than forest areas.

Roads and rivers. Both of these datasets are from IMAZON (2000b, 2000c) drawing on IBGE (1997) and other sources. For the purposes of the current analysis, "principal" roads are federal highways in passable condition.

Pre-1976 disturbance ("antropismo"). These data, based on IBGE (1997), delineate areas subject to loss of vegetation between 1971 and 1976 at a 1:2,500,000 scale. Inspection of the data suggests that areas subject to earlier disturbance are nested within the boundaries of the 1976 *antropismo.*

Land in a protected status. The maps of conservation areas, protected areas, national parks, and indigenous areas are from IBGE (1997).

Agriculture in Amazônia

This section describes broad patterns of land use and land intensity, motivating the subsequent multivariate analysis.

Current Patterns of Land Use and Ownership

Table 1 presents some simple cross-tabulations of land use by precipitation category and distance to the nearest principal road, for those census tracts for which we have precipitation

Table 1. Overview of Study Area

	Annual Rainfall (mm)					
	<1,800	1,800–2,200	2,200–2,600	2,600–3,000	>3,000	Total
			All census tracts			
No. of census tracts	1,409	2,211	1,449	919	106	6,094
Number of farms	118,106	263,274	160,841	116,914	6,546	665,681
Total area (000s hectares)	84,180	183,468	159,054	40,285	19,038	486,025
Protected areas (% of total)	13.6	29.4	20.9	18.1	66.2	24.4
Farm area (% of total)	55.6	28.8	7.1	11.8	1.6	23.9
			% of farm area			
Native forest on farm	26.2	52.2	60.4	41.5	22.2	42.0
Agricultural land	68.8	45.5	37.1	54.5	70.0	54.5
Total pasture	57.1	35.5	23.0	26.1	61.8	42.7
Annual crops	3.6	4.2	2.8	4.2	2.8	3.8
Perennials and trees	0.5	1.0	3.1	3.2	2.0	1.1
Fallow or abandoned	7.5	4.9	8.3	21.0	3.3	7.0
			Census tracts with a portion < 50 km from road			
Total area (000s hectares)	70,695	111,133	71,271	9,219	1,172	263,490
Protected areas (% of total)	12.5	24.6	20.3	4.4	55.1	19.6
Farm area (% of total)	57.9	31.6	10.6	29.3	5.9	32.8
			Census tracts with no portion < 50 km from road			
Total area (000s hectares)	13,485	72,335	87,784	31,066	17,866	222,536
Protected areas (% of total)	19.0	36.7	21.4	22.2	66.9	30.0
Farm area (% of total)	43.5	24.6	4.3	6.6	1.3	13.4

Note: Roads are principal roads of "passable" quality.

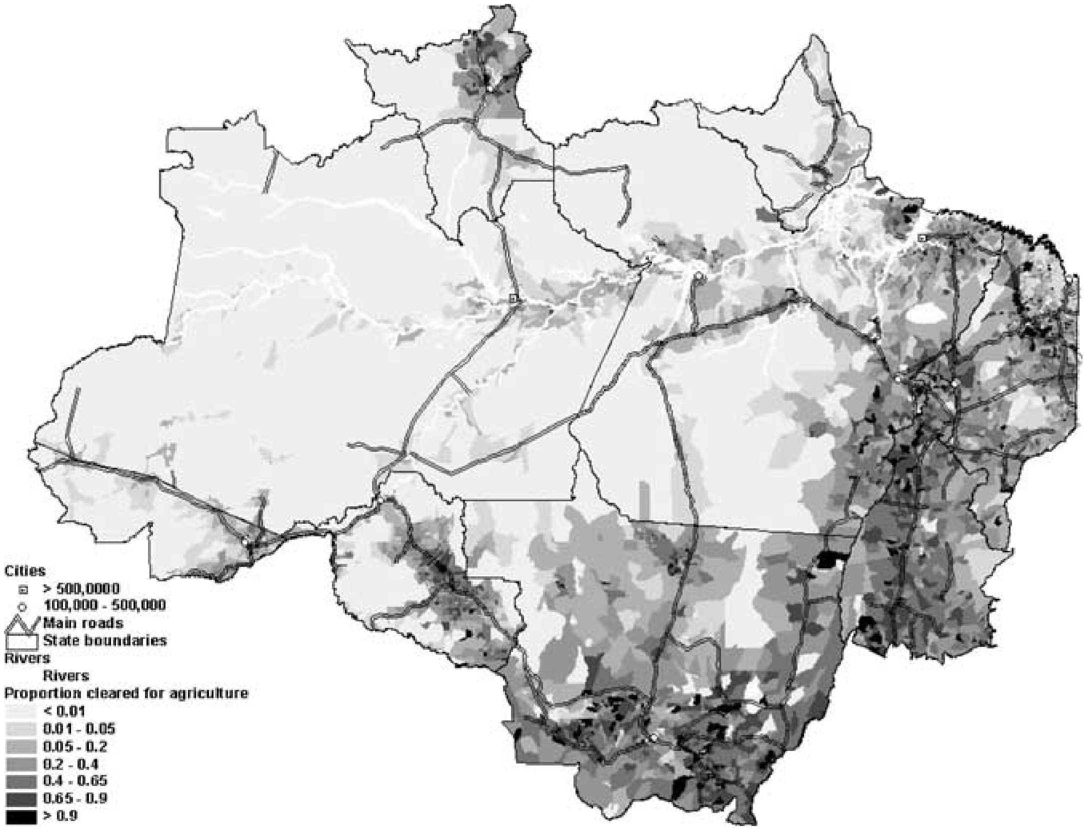
data. The study area includes 486.0 million hectares, of which just under one quarter is in agricultural establishments, with a virtually identical extent in national parks, protected areas, conservation areas, and indigenous areas. Of the area in establishments, 42.0% remains in native forest and 3.5% is not utilizable (e.g., paved or rock-covered). The remaining 54.5%, or about 63.3 million hectares, is in agricultural land.

Census data indicate that the vast majority of agricultural land is devoted to low-value uses. More than three quarters of this land is in pasture, and another tenth is "productive unutilized"—not used in the past four years and probably abandoned, though possibly in long-term fallow. About 7% is in annual crops; much of this is manioc, characterized by high per hectare gross production value but low net revenue per hectare given its high labor input requirements. Only 2% of agricultural land is in perennials or planted forest, often thought of as potentially sustainable and higher-value land uses appropriate to the humid tropics.

Approximately 18.5% of the Amazon receives between 1,290 and 1,800 mm of rain on average; another 38.5% receives between 1,800 and 2,200 mm of rain; and the remaining 43.0% ranges up to around 3,550 mm. Within the driest category, about 55.6% of the land is in establishments; in the middle category, 28.8%; while only 7.5% of the wettest category is in establishments.

There is a sharp drop-off in nonforest land as precipitation increases, a pattern that holds even when controlling for road access. In part this is due to the increased proportion placed under protection in the wettest areas. But the proportion of nonforest land outside protected areas also declines with higher precipitation, with the exception of a local peak in the 2,800 to 3,000 mm range. Does this provide a counterexample to the thesis that high rainfall areas are unfriendly to agriculture? On closer examination, almost all of this high-rainfall agricultural land is near Belém, a city of more than a million inhabitants that has been settled for almost half a millennium. About half of the high-rainfall agricultural land consists of natural grasslands on Marajo Island currently being used for grazing. In other words, these areas do not constitute deforestation, as they were never forested. Of the remaining half, approximately half is unutilized and presumed abandoned.

Map 2 shows the distribution of land cleared for agricultural use. The "Arc of Deforestation" is clearly visible, curving along the



Map 2. Proportion of census tract cleared for agriculture

eastern and southern boundaries of the Basin. In contrast, the areas to the north and west are largely untouched except along the Amazon River and its major tributaries.

Intensity and Value of Land Use

Land values, on average, are low in the Legal Amazon. In June 2002, cropland in Pará, Rondônia, and Mato Grosso sold for US $147, $297 and $454, against a Brazil-wide average of $878 (Fundação Getulio Vargas). A survey by IMAZON undertaken in 2000 (Brito) asked slaughterhouse owners in major cattle-producing regions of the Amazon to estimate the value of improved pasture of different levels of quality. The median estimate for poor quality pasture—representing relatively remote land that had been exploited and was now likely near abandonment due to weed invasions and fertility decline—was about US$ 90/ha. The median estimates for reasonably well-maintained pasture with access to electricity and to good, but seasonably impassable roads was US$ 180/ha; and for land within 50 km of town with all-season accessibility, about US$ 300/ha.

These values are consistent with studies that find small but positive returns to pasture in the Amazon (Mattos and Uhl, Arima and Uhl, Faminow). Arima and Uhl find annual profits ranging from $23/ha (small dairy farmers) to $7/ha (self-reproducing herd, medium-to-very-large ranches in upland areas) to $20–$25 per hectare (range-fattening operations, medium-to-very-large ranches).

We are interested in studying spatial variation in these land values. Unfortunately, direct valuation data are limited. We therefore use a variety of proxies for land value. Deforestation itself is a crude proxy, on the assumption that land with higher potential value is more likely to be converted to agriculture. An alternative proxy, given the importance of pasture, is the stocking density (cattle/hectare of pasture). In general, one would expect better-endowed land, or land closer to markets, to profitably support more cattle per hectare. This is admittedly an imperfect proxy for several reasons. First, natural pasture with a low stocking

Table 2. Size Distribution of Agricultural Establishments

	Total Land Area of Farms (hectares)				
	No Size Given	0–20	20–500	500–2000	2000+
Number of establishments	16,873	480,732	362,940	23,662	8,921
Area of estabs. (000s ha)	NA	1,789	32,848	22,168	63,645
Percent in agricultural land	NA	74.5	59.3	59.7	49.1
Gross value of agricultural production (millions reais)	16.0	883.4	1,750.4	896.4	1,464.1

rate may possibly be more profitable (and thus command a higher price) than planted pasture with a higher stocking rate. Second, very high stocking rates may indicate unsustainable overgrazing, or stall-feeding. Finally, small subsistence-oriented farms of a few hectares may not be comparable to larger establishments, and stocking rate estimates are very sensitive to errors in measuring pasture area for these farms. Nonetheless, the stocking rate provides a simple and intuitively appealing metric for assessing land use intensity across much of Amazônia.

Overall, statistics on stocking rate show very low levels of pasture utilization. About 40% of currently utilized pasture in the Legal Amazon has a stocking rate of less than 0.5 (i.e., two hectares per animal); the mean for this area is 0.3. (The denominator does not include abandoned or fallow areas; their inclusion would bring the rate down substantially). In the remaining 60%, the mean stocking rate is about 0.95.

Land Ownership

Many studies of agriculture and deforestation in Amazônia have examined the behavior of smallholder colonists. An understanding of this group is crucial to assessing the welfare of the Amazônian rural population, and provides a good picture of deforestation dynamics in certain areas. However, these studies provide little comprehensive insight into Amazônian land use, because smallholders control only a small proportion of the land.

In fact, land in the nine Amazônian states is overwhelmingly concentrated in large holdings (see table 2, which includes areas of Maranhão and Tocantins outside the Legal Amazon).[3] While only about 1% of all establishments have more than 2,000 hectares, these establishments control 52.7% of private land and account for 46.8% of all land converted from forest or cerrado to agricultural use. In contrast, establishments with less than 20 hectares constitute 53.8% of the total number of establishments, but control only about 1.5% of the property or agricultural land.

There are few studies of largeholder behavior, presumably because access to these individuals is more difficult for researchers. Hence statistical studies such as the present one provide one of the few means of examining the behavior of largeholders.

Determinants of Deforestation

Spatial Models of Deforestation

A growing set of econometric studies (Chomitz and Gray; Nelson and Hellerstein; Pfaff; Deininger and Minten; Cropper, Puri, and Griffiths; Nelson, Harris, and Stone; Mertens et al.) seeks to understand the determinants of tropical deforestation using spatially explicit data on land cover and land characteristics. These studies generally adopt a simple static model of land use in which a plot of land is converted to agriculture if potential agricultural revenues exceed production and clearing costs. Since direct measures of potential revenues and costs are generally lacking, the studies estimate reduced-form models based on the determinants of revenues and costs, including market accessibility (proxied by road and city proximity) and agroclimatic conditions. Fine-scale spatial data yield cross-variation in these explanatory variables that would be obscured in more aggregate data. The studies find, in general, that deforestation is associated with road proximity, favorable soils, and level terrain, though the magnitude of these effects is highly context dependent.

Previous Amazônia-Wide Studies

Previous econometric studies of Amazônian deforestation have used *município*-level data,

[3] This table based on tabulations of *município*-level data from IBGE.

often combining economic data from the Census with land cover data obtained from remote sensing. Because Amazônian *municípios* range in size up to 160,000 square kilometers, these studies have limited spatial resolution. Early multivariate studies (Reis and Margulis, Reis and Guzmán) focused on the impact of population, agricultural output, and road density. Agroclimatic controls were limited to broad indicators of biome (e.g. forest vs. *cerrado*). Andersen et al. use *municipio*-level data to examine growth in cleared land, rather than levels; they have only a dummy variable for high rainfall, though vegetation-class data may serve as a proxy for agroclimate. Pfaff's study uses a remote-sensing classification of land cover into three categories: forested, cleared forest, and never forested (primarily *cerrado*). The proportion of cleared forest is computed by *município* (excluding *cerrado* from numerator and denominator) and regressed on density measures for roads, rivers, population, development projects, credit agencies, cerrado, and soil nitrogen, along with industrial wage. Pooling data across two years, the analysis has 480 observations. It finds most parameters to be statistically significant but small in magnitude. For instance, a standard deviation increase of 2 in nitrogen density was estimated to expand the deforested area in the *município* by 1.5 percentage points; a similar increase in paved-road density would increase deforested area by 2.1%.

Model

To explain spatial variation in land use, we apply the simple static model of Chomitz and Gray: propensity to clear land depends on the potential profits (or land rent) per hectare from converting the land to agricultural use. Potential profits $\pi(\mathbf{X})$ vary over space as a function of:

- *farmgate prices*, which are related to road, river, and city proximity.
- *costs of clearing*, which we expect to be higher in forest areas than in *cerrado* areas. We also expect that protected area status increases the cost of clearing.
- *revenue from clearing*, which will be higher in forest-biome areas, closer to roads.
- *agroclimatic suitability*. Agricultural productivity depends on soil quality and climate. This relation differs among agricultural products: conditions favoring perennials may not favor pasture, for instance. In general, however, we expect that soils with the more serious physical and chemical constraints will discourage pasture and annual crops. We also hypothesize that high levels of precipitation will discourage these land uses.
- *proximity to prior clearing*. Proximity to prior clearing boosts the attractiveness of current clearing in a variety of ways. Areas that have been settled longer offer markets for inputs (especially labor) and outputs (such as dairy products); may offer health and education services; and may have more secure enforcement of property rights.

Given random variation of land quality within a *município*, the proportion of land p that can profitably be converted to a particular land use is an increasing function of profitability. Pfaff assumes that within *município* i, the profitability at point j is given by

$$\pi_{ij} = \pi_i(\mathbf{X}_i) + \varepsilon_{ij}$$

where $\pi_i(\mathbf{X}_i)$ is a *município* mean and $\mathbf{X}_i$ a vector of *município*-level explanatory variables. Hence he shows that the deforested proportion p_i of *município* i is given by

$$(1) \qquad p_i = F[\pi_i(\mathbf{X}_i)].$$

If the ε_{ij} are independently and identically distributed with a logistic cumulative distribution function, then

$$\text{logit}(p_i) = p_i/(1 - p_i) = \pi_i(\mathbf{X}_i)$$

and it is this equation that Pfaff estimates, adding a homoskedastic *município*-level error term.

This convenient but restrictive assumption about ε_{ij} (or equivalently about the function F) is inapplicable to the finer scale observational units used in this study, since some census tracts have no clearance at all ($p_i = 0$) and some are fully cleared.

This motivates a simple tobit model, in which p_i^*, the latent variable, equals $\mathbf{X}_i\boldsymbol{\beta} + u_i$; and the observed variable, $p_i = 0$, if $p_i^* < 0$; $p_i = 1$, if $p_i^* > 1$; $p_i = p_i^*$, otherwise. This corresponds to a more general form for $F(\cdot)$ in equation (1). Censoring at zero captures the intuition that there will be no conversion in unprofitable areas and the reality that many census tracts lack any agricultural land. Censoring at 1 is necessary because clearance cannot exceed 100%, although $p^* > 1$ indicates profitability above the level sufficient to induce full clearance. Censoring at 1 is necessary also because the measured proportion of cleared land exceeds unity for about 3.7% of the observations. This occurs, for instance, when the entire area of a large farm that straddles census tract borders is assigned to a small census tract containing the farm residence.

Tobit estimates may be inconsistent if the disturbance term is incorrectly assumed to be homoskedastic. We allow this term to be heteroskedastic, due to heterogeneity of agroclimatic conditions within and between census tracts. Measurement error leads also to heteroskedasticity. For instance, census tracts with high perimeter-to-area ratios may have greater variability due to "spillover" effects from neighboring census tracts, such as the border-straddling problem described above. We therefore specify standard deviation $\sigma_{ui} = \exp(\mathbf{Z}_i \boldsymbol{\alpha})$, where $\mathbf{Z}_i$ is a matrix of variables that potentially describes the heteroskedasticity and includes a column of ones.

A shortcoming of this specification is that it fails to account for spatial autocorrelation of the error term, as might result from the omission of spatially autocorrelated variables. We are not aware of any technique for incorporating spatial autocorrelation in the context of a heteroscedastic tobit. Consequently, as a test of the robustness of our results we also estimate a linear regression incorporating a spatial error model:

$$(2) \quad \begin{aligned} \boldsymbol{p} &= \mathbf{X}\boldsymbol{\beta} + \boldsymbol{e} \\ \boldsymbol{e} &= \lambda \mathbf{W}\boldsymbol{e} + \boldsymbol{u} \end{aligned}$$

where the weight matrix $\mathbf{W}$ has $w_{ik} = 1$ if census tracts i and k are neighbors, $w_{ik} = 0$ otherwise, and where the u_i are independently and identically normally distributed.

Analysis of Land Use

The results are presented in table 3. Using variables such as rainfall to explain both the mean and the variance makes it difficult to directly interpret the coefficients. To see this more clearly, note that for our doubly censored regression, the expected rate of conversion for a census tract is given by

$$(3) \quad \begin{aligned} E(y_i \mid \mathbf{X}_i, \mathbf{Z}_i) = \mu(\mathbf{X}_i)(\Phi_1 - \Phi_0) \\ - \sigma(\mathbf{Z}_i)(\phi_1 - \phi_0) \\ + (1 - \Phi_1) \end{aligned}$$

where we write $\mu(\mathbf{X}_i)$ for $\mathbf{X}_i\beta$ and $\sigma(\mathbf{Z}_i)$ for $\exp(\mathbf{Z}_i\alpha)$, where Φ represents the normal cumulative distribution function and ϕ represents the normal probability density function; and where $\Phi_1 = \Phi((1 - \mu(\mathbf{X}_i))/\sigma(\mathbf{Z}_i))$, $\Phi_0 = \Phi((0 - \mu(\mathbf{X}_i))/\sigma(\mathbf{Z}_i))$, $\phi_1 = \phi((1 - \mu(\mathbf{X}_i))/\sigma(\mathbf{Z}_i))$, and $\phi_0 = \phi((0 - \mu(\mathbf{X}_i))/\sigma(\mathbf{Z}_i))$.

If a variable x is part of both $\mathbf{X}$ and $\mathbf{Z}$, then the marginal effect of a change in x on the dependent variable is given by

$$(4) \quad \begin{aligned} \frac{\partial E(y_i \mid \mathbf{X}_i, \mathbf{Z}_i)}{\partial x} = \frac{\partial \mu(\mathbf{X}_i)}{\partial x}(\Phi_1 - \Phi_0) \\ - \frac{\partial \sigma(\mathbf{Z}_i)}{\partial x}(\phi_1 - \phi_0). \end{aligned}$$

Therefore we cannot interpret the results of table 3 without first computing the magnitude of each component of (3) or (4). We do this in figure 1, which shows the predicted proportion of land converted to agriculture as function of rainfall, proximity to pre-1976 disturbance, and protection, with other variables held constant at representative levels.[4]

As expected, areas subject to pre-1976 disturbance show very high proportions of current agricultural land use. At 1,400 mm of rain, 77% of land of this type is predicted to be in agriculture. The proportion declines steadily with increasing rainfall, reaching 16% at 3,400 mm. Areas just outside pre-1976 disturbance locations show a similar but lower curve, declining from 61% at 1,400 mm to just 3% at 3,400 mm. Areas more than 50 km from pre-1976 disturbance have lower conversion rates than closer-in areas with lower precipitation levels, but are similar for areas above 2,700 mm. The marginal reduction in agricultural proportion per mm of rainfall is significantly negative throughout for the areas between 1 and 50 km from the pre-1976 disturbance, ranging from −0.00073 (z-statistic = 16.3) at 1,400 mm to −0.00011 (z = 6.1) at 2,600 mm to −0.00023 (z = 2.3) at 3,400 mm. Areas subject to some form of protection have positive but markedly lower conversion rates than unprotected areas at low rainfall levels.[5] Conversion of protected areas decreases toward a minimum of 9% at 2,200 mm. At higher rainfall levels, formal protection appears to have little impact relative to the low

[4] Location in Pará state, between 100 and 250 km from a city; in forest biome; soil that has low nutrient-holding capacity.

[5] It is possible, of course, that protected areas have been situated in agriculturally unattractive areas, and that this is not detected by our available measures of agroclimatic suitability (see Cropper, Puri, and Griffiths).

Table 3. Regressions on Proportion of Land Cleared for Agriculture

	Tobit		Spatial Error Model	
	Parameter	*t*-stat	Parameter	*t*-stat
Proximity to land cleared by 1976: proportion of census tract in				
Within pre-1976 disturbance area	0.6741	7.58	0.4025	4.45
Within times annual rain in mm	−1.66E-04	−4.83	−8.68E-05	−2.21
in 50 km buffer	0.3244	7.61	0.0927	1.40
in 50 km buffer times annual rain in mm	−1.15E-04	−5.96	−1.04E-05	−0.33
Proportion in protected areas	−0.3876	−10.17	−0.3878	−5.18
Proportion in protected areas, times rain	1.37E-04	9.00	1.29E-04	3.72
Rain (mm), measured at centroid	−4.31E-03	−11.14	−2.86E-03	−28.6
Rain squared	1.66E-06	10.71	9.53E-07	NA
Rain cubed	−2.12E-10	−10.32	−1.03E-10	NA
Proportion in 50 km buffer on main roads	0.0456	7.51	0.0532	4.82
Buffers around cities with populations >25,000, proportion of census tract in				
0–50 km	0.1986	18.77	0.1952	8.55
50–100 km	0.0969	11.31	0.1109	5.11
100–250 km	0.0165	2.70	0.0335	1.67
Buffers around cities with populations >100,000, proportion of census tract in				
0–50 km	−0.1607	−8.40	−0.1308	−5.18
50–100 km	−0.0480	−4.05	−0.0355	−1.91
100–250 km	−0.0100	−1.69	−0.0147	−1.17
Proportion in cerrado vegetation zone	0.1406	10.66	0.0463	2.70
λ (spatial autocorrelation parameter)	NA		0.4760	92.8

Notes: (1) Because of space limitations, we do not report parameter estimates for the intercept, the soil classes, pioneer and cerrado-forest vegetation zones, buffers around rivers or the terms used in approximating the heteroscedasticity in the Tobit, which included square root of area; the ratio of perimeter to area, and its square; vegetation classes; nearness to clearing in 1976; rainfall; and proportion in protected areas. (2) Tobit was censored at 0 and 1. (3) Regressions were on those sectors located west of 45 degrees west, because we did not have rainfall data east of that line. We also excluded those census tracts with ten or more sectors merged together (an indicator of being an urban area). (4) Numerical methods used for estimating the spatial error model did not yield positive variances for polynomial coefficients of rainfall.

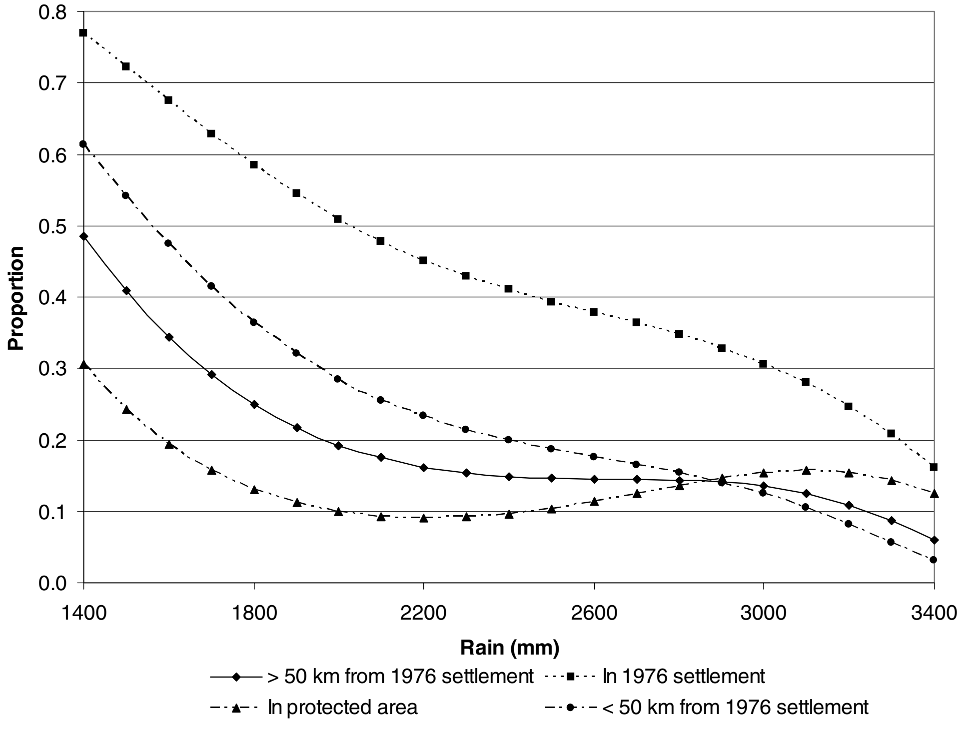


Figure 1. Predicted effect of rainfall on proportion of census tract cleared for agriculture

conversion rates in unprotected areas. A slight increase in conversion of protected areas, as rainfall increases toward very moist levels, may be an artifact of the simple linear functional form used to represent the interaction of protection with rainfall.

Proximity to principal roads has a surprisingly mild measured effect. Location within 50 km of a passable principal road boosts the tobit index (i.e., $\mathbf{X\beta}$) by about 0.05. We believe that this coefficient understates the impact of roads, for several reasons. First, we took a very conservative approach to road inclusion, using only those principal roads which, arguably, could be taken as exogenous causal drivers of land use change. We excluded secondary roads because some of them may represent responses to agricultural development, rather than causes. However, this exclusion is almost certainly too severe—many of these roads did in fact stimulate subsequent agricultural development, and for this reason the measured road effect is underestimated. Second, we did not adjust for the length of time that the road has been in place. Recently constructed roads will have less measured impact. Third, most road effects probably occur within 25 km. Because the census tracts are relatively large, and because registration of the census tract boundaries is subject to some error, road impacts may be obscured. Impacts might be much easier to measure using remote sensing data with fine resolution. Finally, as noted above, the impact of roads may be confounded with the impact of prior clearing. When the variables measuring earlier settlement are removed from the regression, the road coefficients are boosted by about 50%.

Small cities—those of 25,000 to 100,000 inhabitants—have a very strong impact on agricultural use of surrounding areas, boosting the tobit index by 0.20 for areas within 50 km. Larger cities actually had much smaller impacts, perhaps because land is converted to settlements and hence does not appear in the agricultural use measure. Location in the *cerrado* biome had a very strong and significant effect, boosting the index by 0.14. Several of the soil categories had significant and substantial impacts. Shallow soils, for instance, reduced the index by 0.097 (relative to soils with low organic matter, the omitted category), while high-aluminum soils, surprisingly, boosted the index by 0.12. Areas near rivers had somewhat lower agricultural use, other things equal—but riverine associations with soil types may complicate the interpretation of this finding.

The estimate showed strong but patterned heteroskedasticity. The perimeter/area ratio was, as hypothesized, a very strong source of heteroskedasticity.

An alternative specification (not shown) introduced dummy variables for states to capture potential policy differences. Other things being constant, Acre had significantly and substantially less deforestation, and Tocantins more deforestation, than the other states. Inclusion of state dummies reduced the magnitude of the *cerrado* effect, but had no qualitative impact on the relation between rainfall and agricultural use.

To assess whether the results reported in column 1 of table 3 are affected by spatial autocorrelation, we applied the generalized Moran I test devised by Kelejian and Prucha—to our knowledge, the first such application to a two-limit tobit or to a tobit with heteroskedasticity. The test soundly rejected the hypothesis of no spatial autocorrelation, with $z = 30.6$, which is clearly statistically significant at the 1% level. To assess the robustness of the results, we estimated the linear spatial error model (2), with clearance proportion again censored at 1. The results are shown in the second column of the table. The results are qualitatively unchanged. Inclusion of uncensored values for proportion cleared resulted in lower *t*-statistics but similar coefficients.

Finally, we split the sample into western (Acre, Amazônia, Rondônia, Roraima) and eastern states.[6] These regions have different settlement histories and densities, but both exhibit wide ranges of rainfall. In the western sample, predicted clearance proportion declined monotonically with increasing rainfall. In the eastern sample, predicted clearance rates declined sharply (outside protected areas) with increasing rainfall to a minimum at about 2,600 mm. Predicted rates increased slightly at higher rainfall levels (but more sharply for protected areas), apparently reflecting the historical and ecological peculiarities of the Belém region, noted earlier.

Analysis of Stocking Rate

To examine the determinants of land value, we concentrate on the stocking ratio as an objective, easily understood proxy. We ask, first, what determines the location of a commercially oriented pasture (proxied by mean

[6] We thank an anonymous referee for suggesting this robustness test.

pasture size greater than 5 hectares)? Then: within these areas, what are the determinants of the stocking ratio?

We set this up as a sample-selection problem:

$$r = \mathbf{X}\beta + u$$
$$y^* = \mathbf{Z}\gamma + e$$
$$y^* > 0 \Rightarrow y = 1; y \leq 0 \Rightarrow y = 0$$

where r is the natural logarithm of the stocking ratio, $y = 1$ is an indicator that pasture exists and mean pasture size is greater than 5 hectares, u and e are unobserved, possibly correlated, disturbances, and the stocking ratio equation is estimated only when $y = 1$. The correlation of the disturbances allows for the possibility that areas with pasture greater than 5 hectares may be systematically different from other areas, controlling for observed variables. We specify that the presence of protected areas affects the likelihood of finding large pastures (as opposed to finding small pastures or none at all) but does not affect the stocking rate on converted land. A maximum likelihood estimate of the sample selection model did not reject the hypothesis of independence between the two equations. We therefore independently reestimated the stocking rate equation.

Table 4 shows alternative estimates of the stocking ratio equation. The specification in the second column includes farm size and the ratio of unpaid labor to farm area as exogenous explanatory variables. Holding agroclimatic conditions constant, a 10% increase in farm size reduces the stocking rate by about 1.7%, while a 10% increase in the ratio of family labor to agricultural land increases the stocking rate by about 4%. Assuming unpaid family labor does not increase with farm size, a 500-hectare farm is predicted to have a stocking rate 39% lower than a 50-hectare farm.

Nonclimatic locational variables significantly affect the stocking rate. Other things being equal, location in the *cerrado* decreases stocking rates by 38%. Roraima and Amapá have substantially lower stocking densities, other things being equal, than the other states. Para, Tocantins, and Maranhão have somewhat lower stocking densities than Acre, Rondonia, and Amazonas. Proximity to passable roads boosts the stocking rate by about 10%, and location within areas subject to pre-1976 disturbance boosts the stocking rate an additional 15%. This is an encouraging sign that pasture use intensifies over time. But the coefficient on past disturbance may also capture road and market access impacts. Location within 50 kilometers of a medium-sized city boosts the stocking rate a further 16%. However, location near a large city tends to substantially reduce the stocking rate. This is surprising, given the presumed effect of urban

Table 4. Regressions on Natural Log of Stocking Density

Variables	Parameter	*t*-stat	Parameter	*t*-stat
Ln (household labor/hectare of cleared land)	NA	–	0.0398	2.26
Ln (mean establishment size)	NA	–	−0.1723	−9.58
Proportion in pre-1976 disturbance area	0.2402	4.78	0.1350	2.79
Proportion in 50 km buffer around area	0.0243	0.77	0.0248	0.83
Rain (mm), measured at centroid	6.44E-04	1.31	4.56E-04	0.99
Rain squared	−2.20E-07	−2.03	−2.15E-07	−2.11
Proportion in 50 km buffer on main roads	0.1121	3.66	0.0995	3.46
Proportion in 0–25 km zone from main river	0.1377	2.60	0.0486	0.97
Proportion in 25–50 km zone from main river	0.1578	2.42	0.1590	2.59
Buffers around cities with populations >25,000, proportion of census tract in				
0–50 km	0.1990	2.79	0.1490	2.20
50–100 km	0.0628	0.89	0.0524	0.79
100–250 km	−0.1232	−1.81	−0.0610	−0.95
Buffers around cities with populations >100,000, proportion of census tract in				
0–50 km	−0.3085	−4.88	−0.3247	−5.45
50–100 km	−0.1081	−2.19	−0.1002	−2.15
100–250 km	−0.0069	−0.22	−0.0338	−1.12
Proportion in *cerrado*—vegetation zone	−0.5821	−11.83	−0.4675	−10.01
Proportion in *cerrado*—forest zone	−0.1809	−3.18	−0.1379	−2.58

Notes: (1) Because of space limitations, did not report parameter estimates for the intercept, the soil classes, or the pioneer vegetation zone. (2) Regressions were on those sectors located west of 45 degrees west. Excluded were those with less than 5 hectares of pasture; those with ten or more sectors merged together (an indicator of being an urban area); and those with stocking density greater than 10 cows per hectare.

demand on dairy farming, and requires further investigation, but it may simply reflect the poor agroclimatic conditions surrounding Manaus and Belém.

Holding these and other factors such as soil type constant, increasing rainfall is strongly and significantly associated with lower stocking rates. An increase in precipitation from 1,600 to 2,400 mm reduces stocking rate by 27%.

The first column shows an alternative specification, dropping farm size and labor utilization. (This treats them as endogenously determined by the agroclimatic and market variables.) This slightly attenuates the effect of rainfall, since smaller farms are found in the more humid areas. It sharpens the effect of roads and previous disturbance. Nonetheless, an increase in precipitation from 1,600 to 2,400 mm is still associated with a 17% decrease in the stocking rate.

Discussion and Conclusions

Deforestation in Amazônia has led overwhelmingly to the creation of extensive pasture, concentrated in large holdings and located mostly in the less humid regions of the basin. Productivity of this land is on average low. Bivariate and multivariate analyses show that the probability that land is currently claimed, or used for agriculture, or intensively stocked with cattle, declines substantially with increasing precipitation levels, holding other factors constant—including road access and proximity to prior disturbance. Proxies for land abandonment are higher in high rainfall areas. Taken together, these findings suggest that the returns to agriculture in the more humid regions have been lower than in Amazônia as a whole. These results are consistent with agronomic hypotheses that high precipitation levels discourage cattle raising and cultivation of annual crops.

This analysis of past experience sounds a strong cautionary note: a continuation of past agricultural practices is unlikely to be successful in developing the wetter western regions of the Amazon basin. It is possible, of course, that new technologies and institutions could provide favorable models for agricultural development in the Western Amazon, and there are indications that perennial cultivation could be suitable. However, the findings imply at least that the agricultural opportunity costs of avoiding pasture are low.

The findings also draw attention to the way in which settlement and disturbance patterns shape the evolution of subsequent deforestation and agriculture. The results suggest that in less humid areas, roads, colonization schemes, and other disturbances sharply increase subsequent deforestation. As shown in Nepstad et al., clearance in these drier areas is more likely to result in runaway fires. In addition, the *cerrado* in these areas may be more biologically unique, and more threatened, than more moist forest areas. While some of these areas offer relatively high agricultural returns—especially around medium-sized cities and in places suitable for soybeans—others are destined for pasture with very low stocking rates. Ongoing discussions of implementing large-scale tradeable development rights schemes in Brazil (Chomitz, Bernardes) may point to a low-cost way of reconciling development and conservation goals in these areas.

In more humid areas, roads and settlement have a smaller impact because of the inherent unattractiveness of the land. However, the predicted long-term impact of settlements in these areas is large enough to raise the prospect of significant forest fragmentation and disruption of ecological processes.

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