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Geographic Patterns of Land Use and Land Intensity in the Brazilian Amazon

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Nearly 90 percent of agricultural land in the Brazilian Amazon is used for pasture, or has been cleared and left unused. Pasture on average is used with very low productivity. Analysis based on census tract data shows that agricultural conversion of forested areas in the wetter Western Amazon would be even less productive, using current technologies.

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Summary findings

Using census tract data from the Censo Agropecuario 1995–96, Chomitz and Thomas map indicators of current land use and agricultural productivity across Brazil's Legal Amazon. These data permit geographical resolution about 10 times finer than afforded by *municipio* data used in previous studies. Chomitz and Thomas focus on the extent and productivity of pasture, the dominant land use in Amazonia today.

Simple tabulations suggest that most agricultural land in Amazonia yields little private economic value. Nearly 90 percent of agricultural land is either devoted to pasture or has been out of use for more than four years. About 40 percent of the currently used pastureland has a stocking ratio of less than 0.5 cattle per hectare. Tabulations also show a skewed distribution of land ownership: almost half of Amazonian farmland is located in the 1 percent of properties that contain more than 2,000 hectares.

Multivariate analyses relate forest conversion and pasture productivity to precipitation, soil quality, infrastructure and market access, proximity to past conversion, and protection status. Chomitz and Thomas find precipitation to have a strong deterrent effect on agriculture. 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 (such as road access) constant. Proxies for land abandonment are also higher in high rainfall areas. Together these findings suggest that the wetter Western Amazon is inhospitable to exploitation for pasture, using current technologies.

On the other hand, land conversion and stocking rates are positively correlated with proximity to past clearing. This suggests that in the areas of active deforestation in eastern Amazonia, the frontier is not "hollow" and land use intensifies over time. But this area remains a mosaic of lands with higher and lower potential agricultural value.

This paper—a product of Infrastructure and Environment, Development Research Group—is part of a larger effort in the group to understand the causes and consequences of land use change. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Shannon Hendrickson, room MC3-640, telephone 202-473-7118, fax 202-522-0932, email address shendrickson@worldbank.org. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The authors may be contacted at kchomitz@worldbank.org or tthomas2@worldbank.org. October 2001. (38 pages)

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Comments on this working paper are welcome and may be sent to: kchomitz@worldbank.org

Tables, Maps and Figures

Note: tables, maps and figures follow the text.

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[1] Maps in color are available on the Policy Research Working Papers Web site.

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Motivation and goals

Policies affecting development in Amazônia must balance a variety of competing options for land use. These include pasture, crops, agroforestry, sustainable forest management, provision of environmental services, and conservation to maintain future options. Because conversion to some kinds of agriculture may preclude the option to devote the land to other uses in the future, it is important to know:

- How public policies, especially with regard to infrastructure, affect the likelihood that land will be converted to different kinds of agriculture.
- The potential economic benefits of conversion to agriculture.

The potential economic and noneconomic values of the land vary dramatically from place to place, Mapping these variations can help us to understand which biophysical and socioeconomic conditions favor productive agriculture, and to identify conditions under which land is at risk of being converted to relatively unproductive agriculture.

As a modest first step, this paper uses census-tract-level data from the *Censo Agropecuario 1995-96* (IBGE, 1998) to map indicators of current land use and agricultural productivity across the Legal Amazon of Brazil. It relates these indicators to market proximity, infrastructure access, and agroclimatic conditions. It focuses particularly on pasture for two reasons. First, pasture is by far the dominant land use in Amazônia today, accounting for more than three-quarters of agricultural land use. Second, this land use is characterized on average by low productivity and low employment absorption, suggesting that in many cases it may not be a socially optimal use of the land.

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

The paper begins with a description of the biogeophysical and socioeconomic context. It then describes broad patterns of land use in Amazônia, using simple descriptive statistics and maps. 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 finding and discusses their implications.

The biogeophysical and socioeconomic context

This section describes some of the basic features of the region – natural and human -- that shape patterns of land use. The data described here constitute the main explanatory variables for the multivariate analysis.

Climate, soils, and natural vegetation

Agriculture is constrained by biogeophysical factors: climate and soils. Sombroek (1999) hypothesizes that high rainfall and lack of a dry season are important limiting factors to agriculture in Amazônia. In high rainfall areas, he claims, humans and animals are more susceptible to disease;

forest burning is incomplete, complicating the establishment of crops or pasture; grains and many other crops such as soybeans, are subject to rotting; mechanization is difficult; and rural access roads are difficult to build and maintain. 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 (ANEEL) to 0.05 degrees spatial resolution. Map 1 shows the mean annual precipitation based on this data. There is a strong gradient from high precipitation in northwest towards lower precipitation in the southeast, with an additional rainfall peak in the northeast. 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 percent of the land area of the Legal Amazon).

Another important class of biogeophysical parameters are those related to soil types. There are many different ways to classify soils based on their many underlying properties (such as texture, slope, parent material, depth, and soil moisture and temperature regimes). Map 2 was kindly provided by the Soil Survey Division of World Soil Resources of the U.S. Department of Agriculture (Eswaran and Reich, nd). It summarizes the soils by their primary limiting factor. In our study area, the data distinguish thirteen soil categories, though worldwide their system notes about twice that many.

Map 3 shows the Vegetation Map of Brazil (Ministerio da Agricultura, et al, 1988, and digitized by USGS EROS Data Center). While natural vegetation may itself reflect soil and climatic characteristics, it may provide additional biogeophysical and economic information related to the ease and attractiveness of converting the land to agricultural use. To take an obvious example, cerrado will have lower costs of clearing, but also lower revenues from sale of timber, than forest areas.

The socioeconomic context

Land use in Amazônia – and in virtually all regions of agricultural expansion, worldwide – is strongly shaped by past settlement patterns and by roads (Reis and Margulis, 1991; Chomitz and Gray, 1996; Angelsen and Kaimowitz, 1999). Alves (1999), for instance, shows that deforestation in the Amazon has tended to expand from areas already deforested by 1978. Map 7 shows the progressive extent of clearing, based on remote sensing data. The relatively small amount of clearing in 1976 is a strong predictor of current land use, as will be seen below. Principal roads are shown in Map 4; their relation to agriculture is evident on inspection. Pfaff (1997) uses multivariate analysis to show that proximity to roads is indeed a strong predictor of deforestation in Amazônia.

Protected areas can also shape land use, though their efficacy in deterring settlement has been questioned. Map 5 shows the substantial area under protection as indigenous lands or for conservation. The multivariate analysis later in this paper allows an estimate of the actual deterrent effect of protected status.

Agriculture in Amazônia

This section describes broad patterns of land use and agricultural output in Amazônia, using data from the *Censo Agropecuário 1995-1996* (IBGE, 1998). We are extremely grateful to the *Instituto Brasileiro de Geografia e Estatística* (IBGE) for providing us with tabulations of land use, production, labor, and cattle at the level of the census tract (*setor*), along with census tract boundary maps. We merged very small sectors (less than 400 hectares) with adjacent sectors, yielding 6776 sectors or agglomerates as the units of analysis. This permits geographical resolution about 10 times finer than afforded by municipio data that has been the subject of previous study. We rely also on some tabulations of municipio- and state-level data for variables and establishment-size breakdowns not available in the census tract data.

Geographical patterns of land use and production

Land use

Table 4 presents basic statistics on land ownership and use in the Legal Amazon. The study area includes 492.7 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, 41.5 percent remains in native forest, 55.0 percent is in agricultural land, and the remaining 3.5 percent is unutilizable (paved, rock-covered, etc.).

A total of 65.3 million hectares is agricultural land; that is, productive land in crops, pasture, plantation forest, or previously used and now abandoned. As we shall in greater detail, the vast majority of this territory devoted to very low-value uses. More than three quarters of this land is in pasture, and another tenth is 'productive unutilized' – probably abandoned. About eight percent 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. Less than 2 percent of agricultural land is in perennials or planted forest, often thought of as potentially sustainable and higher-value land uses.

This paper uses the ratio of agricultural land (as defined above) to census tract area as a measure of deforestation. Some caveats apply, since the Census categories were not designed for this purpose. Based on our reading of the Census interviewers' guide and discussions with IBGE staff, we assume that cerrado is classified as forest unless it is currently used for grazing or agriculture, or has 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). 'Unutilized' areas are defined as those that have not been used for more than four years, and we presume them to be abandoned. However, 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. Figure 1 shows that there were substantial declines between Censuses in the area of establishments in Amazonas and in Acre. Our deforestation estimates will exclude degraded land in any such areas, and will also exclude areas outside current establishments that have lost forest cover because of fires or logging.

As is well known, agricultural land use is largely concentrated along the Arc of Deforestation that curves along the eastern and southern edges of the region. (See Map 13) This is true not only of agricultural land, but of all land in agricultural establishments. Establishments in this region tend to be quite large, ranging up to an average of several thousand hectares in northern Mato Grosso (map 12).

In contrast Map 4 shows that only a negligible proportion of areas in the Western Amazon is in establishments; much is in protected areas. The establishments in this region tend to be quite small (often less than 20 hectares on average) and many are presumably subsistence-oriented. However, wet areas tend to have a higher proportion of their agricultural land in perennial crops (table 4).

The dominance of pasture is shown vividly in Maps 9 to 11, depicting the proportion of natural pasture, planted pasture, and total pasture in agricultural area. Natural pasture areas, as might be expected, correspond closely to areas where the natural vegetation is cerrado or 'pioneer.'

Map 8 shows the proportion of productive but unutilized land. This probably represents abandoned land. It is prevalent along the Western Amazon and around Belém (both high-rainfall areas), but also in Maranhão along the border with Tocantins.

Production

The census-tract level data provide fine geographic detail on land use, but, in our dataset, lack information on specific production commodities or their values. For complementary information on land use, we turn to municipio-level data on production value in Tables 1-3[1] and refer to municipio-level maps of these data (not shown). Gross value of production is dominated by a handful of products: cattle, soybeans, manioc, milk, and logs. These tend to show strong geographic patterns.

Soybeans

Soybeans are concentrated in Mato Grosso and southern Maranhão (Table 1). Soybeans tend to be important where rainfall is between 1,600 and 2,000 mm annually; where there are 3 or 4 consecutive dry months; where the primary soil limiting factor is "high phosphorus, nitrogen, and organic matter retention"; and where the underlying vegetation is *cerrado.*

Milk

Milk is an important product in central Rondônia, as well as the tri-state region of Pará, Tocantins, and Maranhão. The location of dairy production is highly sensitive to road access and proximity of processing plants, though the advent of ultraprocessed milk extends the range for establishing such plants. Most dairy production is in areas with annual precipitation below 2,200 mm.

Manioc

Manioc is often the main crop in census tracts which do not have much agricultural activity, where precipitation is high, and where average establishment size is small. This is true especially in Amazonas, but also in central and western Pará, and parts of Acre and Amapá. These are presumably frontier regions where manioc is largely a subsistence crop. We note, however, areas near the coast in northeast Pará and northern Maranhão, as well as other places such as south-

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[1] Tables 1 and 2 are taken directly from state-level agricultural census data, and include data for the entire state, even though a large part of Maranhão and a small part of Tocantins are not in the Legal Amazon. Table 3 includes only the census tracts in the Legal Amazon that are west of 45 degrees West, and because the data is extracted from municipio data, did not include all of the agricultural products that were in Tables 1 and 2. One key commodity excluded was milk. Many other products which may have been locally important but of low importance for the entire Amazon were also excluded.

central Mato Grosso, northern Roraima, and eastern Acre, where overall agricultural land use is relatively high but where manioc constitutes a large share of production.

Cattle

Cattle are a major contributor to the value of production[2] in the southern half of Pará, all but the western part of Mato Grosso, all of Tocantins, and especially the western part of Maranhão; and in parts of Amapá, Roraima, and Acre. In areal terms, cattle are found across a variety of soils and vegetation types, and across a range of precipitation levels. They seem to be concentrated, however, in areas that have at least two consecutive dry months.

Extractive products

In northeast Pará, northern Mato Grosso, and the north and southwest of Amazonas, extractive activities represent a large portion of the agricultural production, though the areas in Amazonas have a very low density of establishments. Logging constitutes most of the extractive activities, though piacaba is important in northern Amazonas.

Land use, rainfall, and roads

Table 4 and Figures 5 through 7 present 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 data. Approximately 40 percent of the Amazon on average receives between 1,300 and 2,000 mm of rain; another 40 percent receives between 2,000 and 2,400 mm or rain; and the remaining 20 percent ranges up to around 3,500 mm. The driest category has 45 percent of the land in establishments; the middle category, 13 percent; while only 8 percent of the wettest category is in establishments.

A striking feature of the figure is the sharp drop-off in nonforest[3] land as precipitation increases. 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. The proportion of all land in agriculture generally declines with increasing rainfall, reaching near zero by 3,200 mm.

It is instructive to examine the apparently anomalous increase in nonforest land in the 2800-3000 mm precipitation 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 the 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. Of the remaining half, approximately half is unutilized and presumed abandoned. This example might be viewed as an 'exception that proves the rule' – non-perennial agricultural development is possible in high rainfall areas, but only in conditions of very high local demand, centuries of effort, and unusual agroecological conditions – and even then with a high failure rate.

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[2] The value of cattle was calculated by adding the value of cattle slaughtered to value of cattle sold, and subtracting value of cattle purchased.

[3] Almost all of this is agricultural land, with a small proportion of 'unutilizable.' Some of the latter category includes settlements, areas paved over, etc.

Figures 6 and 7 show that the association of land use with rainfall is not an artifact of the location of roads; it holds even when census tracts are disaggregated by distance to the nearest principal road. Comparison of the charts suggests that roads do affect the proportion in agriculture, especially in the middle ranges of precipitation.

Production and land use by establishment size class

Land in the nine Amazônian states is overwhelming concentrated in large holdings (see Table 2, which includes areas of Maranhão and Tocantins outside the Legal Amazon; and Figure 4). While only about 1 percent of all establishments have more than 2,000 hectares, these establishments control 52.7 percent of private land and account for 46.8 percent of all land converted from forest or cerrado to agricultural use. In contrast, establishments with less than 20 hectares constitute 53.8 percent of the total number of establishments, but control only about 1.5 percent of the property or agricultural land.

There is strong product differentiation by size class of establishment (Table 2). The smallest farms – those under 10 hectares – appear to be strongly subsistence-oriented, with manioc and rice constituting 30 to 40 percent of production. In the 20 to 100 hectare size range, manioc is still important, but so are cash products such as milk and bananas. For large and very large establishments in the 100 to 100,000 hectare range, cattle and soybeans predominate. Among the few ultralarge establishments of more than 1,000 square kilometers, silviculture is dominant.

Land Value

There is no question that land values, on average, are low in the Legal Amazon. Published data[4] from Receita Federal show the mean declared unimproved land value in the Northern Region[5] was just R$46.84/ha in 1997, as compared to to a Brazil wide average of $339.88. Anecdotal reports suggest typical values, for improved pasture, of R$200/hectare[6].

We are interested in studying spatial variation in these land values. Unfortunately, direct valuation data is limited. Declared property tax data are not available at a disaggregate level, and may be subject to misrepresentation. We use therefore a variety of proxies for land value.

One basic proxy is land scarcity. In regions where only a small proportion of available land has been claimed as private property, it is reasonable to assume that land is so abundant as to have essentially no value. Another way of putting it is that the potential revenue from the land is less than the cost of enforcing claims to it (Schneider, 1995). Land scarcity is shown in Map 4, which depicts the ratio of land in establishments to total non-water area of each census tract. It indicates, as one would expect, more scarcity near cities and roads. This reflects higher farmgate prices of products, lower costs for agricultural inputs, and lower costs of enforcing claims.

This proxy shows tremendous land abundance in the Western Amazon. In the wettest regions of Amazônia, as we have seen, the low ratio of land in establishments goes along with a high proportion of land in protected areas. However, the designation of these areas as protected may reflect, in part, a recognition that these areas are not suitable for agricultural development. In

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[4] http://www.receita.fazenda.gov.br/PessoaJuridica/itr/PerfilITR97/TerraNua.htm#Valor da Terra Nua - UF

[5] Acre, Amapá, Amazonas, Pará, Rondonia, and Roraima.

[6] Eugenio Arima, personal communication, based on a survey in progress.

addition, the extent of land outside protected areas far exceeds the area incorporated in establishments. A closely linked indicator is the proportion of each census tract in agricultural land (that is, converted from natural habitat). On the simple model that land is converted if it has positive value, higher conversion proportions track higher land values. Map 13 shows that this proxy closely tracks the previous one.

For the three quarters of agricultural land in pasture, we would expect that per-hectare profits would provide a guide to land value. Several attempts have been made to assess the profitability of Amazônian pasture using farm models based on interviews with small samples of farmers. A recent and thorough study is that of Arima and Uhl (1997), based on three locations in Pará. They find annual profits ranging from US$23/ha (small dairy farmers) to $7/ha (self-reproducing herd, medium to very large ranches in upland areas) to $20-$25/ha (range-fattening operations, medium to very large ranches). Vosti, Witcover, and Carpentier (1998) report gross revenues of $96/ha for small dairy operations in Acre and Rondonia, about 50 percent higher than the small dairy farmers studied by Arima and Uhl. Annual profits in this range reported by Arima and Uhl, together with assumed land price appreciation due to the growth of markets or improvement of transportation, can provide modest real rates of return on capital (8 to 12 percent), assuming that land is costlessly acquired and financed through sale of timber or through a subsidy of some kind. These rates of return, together with assumed appreciation due to improvements over time in market access, might justify land values in the $60 to $300/ha range.

Because of the difficulty in allocating Census-reported expenses between different activities, we do not attempt to map net revenues from pasture. Instead, we use stocking density (cattle/hectare of pasture) as a proxy for value. 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 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 percent of currently-utilized pasture in the Legal Amazon has a stocking rate of less than 0.5 (that is, 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 percent, the mean stocking rate is about 0.95.

Map 6 shows the average stocking rate by census tract (total cattle divided by total area of pasture – both natural and planted pasture – for the census tract). It excludes census tracts where there are fewer than 5 hectares of pasture per farm with cattle, for the reasons mentioned above. The map shows a trend toward lower stocking density in cerrado areas, with stocking densities below 0.4 cows per hectare in southwest Maranhão, most of Tocantins, northern Roraima, the east half of Amapá, and southern Mato Grosso. The stocking density appears to be relatively high along the main roads in Acre and Rondônia, along the Amazon river in western Pará and eastern Amazonas, in northern Mato Grosso, and in small pockets in other parts of Amazonas, Pará, and Maranhão. As we shall see, stocking rates are sensitive to farm size and to the use of unpaid labor, complicating comparisons across regions where farm sizes vary.

Summary

According to the *Censo Agropecuário*, about one eighth of the Legal Amazon was converted to agricultural use by 1996; this land is overwhelmingly concentrated in the hands of large landholders. Several proxies suggest that utilization and productivity of this land is very low. About one-eighth of the agricultural land is not in current use; of the remainder, ninety percent is in mostly extensive pasture, with low average stocking rates.

Visual inspection of maps, and simple cross-tabulations, suggest that agricultural values in high rainfall areas are particularly low on average. In these areas, only a small fraction of available land has been claimed by agricultural establishments, and a smaller fraction has been converted to agricultural use. In these areas, and in cerrado areas, proxies for land use intensity or value are very low. However, there is some cultivation of potentially high-value perennials in the higher rainfall areas. The next section uses multivariate analysis to assess whether the apparently low potential of high-rainfall and cerrado areas reflects only the lack of roads and settlements, or is a more fundamental reflection of biogeophysical constraints.

Analysis

Land use

Model

What are the determinants of land use and deforestation in the Legal Amazon? Alves (1999) and Pfaff (1997) used remote sensing data on land cover to address this question, with important findings. Alves shows that clearing has tended to expand outwards from its 1978 location. Pfaff, using data summarized at the municipio level, shows the importance of the road network in determining the location of deforestation; this multivariate analysis controls for urban proximity and for nitrogen density of the soil.

The analysis reported here builds on and complements this earlier work. Taking advantage of the *Censo Agropecuário*, it uses reported land *use* (based on census-tract data) rather than remote-sensing based land *cover*. This provides a useful cross-check, since available remote sensing data distinguishes only between forest and nonforest and is subject to classification errors. (For instance, *capoeira* – i.e., regrowth – may be classified as forest.) The work reported here also uses precipitation as an explanatory variable, a key factor not available to earlier work.

The land use data have shortcomings of their own. They are potentially subject to reporting error by the landholders. Our calculation of non-water area in the sectors is subject to registration error in superimposing maps.[7] We assume that areas outside agricultural establishments are in natural vegetation; this will not be true in settled areas which must therefore be excluded from consideration.

To explain spatial variation in land use, we apply the model of Chomitz and Gray (1996): propensity to clear land depends on the potential profits Π (or land rent) per hectare from converting the land to agricultural use. Potential profits depend on:

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[7] We estimate registration to be accurate within approximately plus or minus 2 kilometers.

- *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 (because of expected penalties).
- *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.
- *subsidies and other government policies promoting agriculture.* Unfortunately we have no information on policies that might have had identifiable regional effects, except for road-building. It is not clear that subsidized credit and other incentives had disproportionate impacts on certain regions.

Given random variation of land quality within an observation unit, the proportion of land p that can profitably be converted to a particular land use is an increasing function of mean benefits and a decreasing function of mean costs. In the dynamic context of frontier expansion, where not every profitable situation is yet exploited, the probability of land conversion is related both to the potential profitability of conversion and to another variable, *proximity to prior conversion.* In this simple model

$$p_t = p(\Pi, p_{t-1})$$

A standard functional form for this model is the tobit:

$$p^* = X\beta + u$$

$$p = 0 \text{ if } p^* < 0; \text{ otherwise } p = p^*$$

where X is a vector of explanatory variables representing Π and p, u is a random disturbance term and p^* is a latent variable. 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.

However, the tobit model, while standard, is consistent only if the disturbance term u is homoscedastic. In other words, it assumes that all unobserved variables have the same variance across census tracts. If this assumption fails, the tobit is not trustworthy. Given the great heterogeneity of census tracts in size and other characteristics, the assumption of homoscedasticity is questionable. A spatially autoregressive error structure would also preclude homoscedasticity (Anselin, 1999). We therefore follow the suggestion of Deaton (1997, pp 89-90) that iterated quantile regressions (Powell, 1984, 1986; and Buchinsky, 1994) can be used as a consistent alternative to the tobit. In an iterated quantile regression, the median of p, conditioned on X, is estimated as a linear function of X. Observations for which the predicted value of p is less than zero are then dropped, and the estimate is repeated. The process is iterated until it yields a stable subset of observations. Standard errors are obtained via bootstrapping. The predicted value of $p|X$ is simply:

$$X\beta, \text{ if } X\beta > 0$$

$$0, \text{ if } X\beta \leq 0$$

As Deaton points out, this is a simpler and more appealing representation than the nonlinear function (derived from a probably incorrect assumption about disturbance variances) which arises from a tobit prediction.

Data

The sample of census tracts analyzed consisted census tracts in the Legal Amazon west of 45 degrees West latitude (i.e., those for which precipitation data was available). Some urban census tracts[9] were excluded; however the sample probably includes census tracts with settlements.

The dependent variable was the ratio of agricultural area, as reported by the Census, to computed non-water area of the census tract. 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. We assume that reported proportions greater than 1 should be treated as equal to 1, censoring both the tobit and iterated quantile regressions.

Results

The results are presented in Table 5. The preferred specification is the quantile regression in the middle column. It is helpful to think of the predicted value of the regression as an index corresponding to the expected proportion of the census tract used for agriculture, with the proviso that the expected proportion is zero when the index is negative, and unity when the index is greater than 1. Most of the variables are of the form: proportion of the census tract with a given characteristic or location. Spatial patterns of model predictions, in Map 14, can be compared to actual proportion of agriculture in Map 13.

State dummies were introduced to allow for policy differences between states, but these coefficients also capture some biogeophysical effects, weakening the measured effects of natural vegetation. The most striking divergences among states were a –0.13 differential for Amapá, a +0.06 effect for Mato Grosso and a +0.12 differential for Tocantins, compared to a clustering of the other states. When state dummies are excluded, location in the cerrado is found to have a strong positive effect on agricultural use.

Probably the single most important influence on current agricultural use was proximity to pre-1976 clearing. Other things equal, location in an area that had been cleared by 1976 boosts the index of current agricultural use by 0.43; location in the 50 km band outside the limits of 1976 clearing boosts the index by 0.27; location in the 50 to 200 km band boosts the index by about 0.2. These effects may to a large extent represent road impacts, especially the impacts of secondary roads not otherwise included as explanatory variables. In addition, it is possible that the first spots to be cleared were attractive for reasons not captured in our explanatory variables. To the extent that this

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[9] We considered a census tract polygon as urban if ten or more census tracts had to be combined into one polygon for mapping purposes, due to the small size of the census tracts. We believed the reason for the small size was that the high population density.

is true, early clearing is a proxy for an unmeasured land characteristic. However, the strong effect of early clearing very likely represents a dynamic process of settlement and natural 'sprawl' of development.

Precipitation has a strong, highly significant negative effect, all else constant. For example, consider a location in Pará that has typical soils, is more than 25 km from a principal road, between 100 and 200 km from the nearest location that was already cleared in 1976, and is far from cities. With 1600 mm of rain, the predicted proportion of a census tract in agriculture is 22 percent. That proportion drops to 8 percent at 2000 mm of rain and nearly 0 percent at 2300 mm.

Proximity to principal roads has a surprisingly mild measured effect. Location within 50 km of a good quality principal road boosts the agricultural use index by about 0.06. Location within 25 km of a poor quality road boosts the index also by 0.06. Location at 25 to 50 km from a poor quality principal road appears to have a perverse effect, but this probably reflects the coarseness of road buffer widths[10] and the correlation between the proportion of the census tract at 0 to 25 and 25 to 50 km.

We believe that these coefficients understate 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 30 meter 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 (right column of Table 5), the road coefficients are boosted by about 50 percent.

Areas near rivers had somewhat lower agricultural use, other things equal – but riverine associations with soil types may complicate the interpretation of this finding. Soils in general have detectable but mild impacts on agricultural use, with more marked impacts in a few rather unusual soil types. Protected area status does appear to substantially and significantly deter agricultural use; the effect is not simply due to the location of protected areas in more remote or less agriculturally attractive areas.[11]

Small cities – those of 25,000 to 100,000 population – have a very strong impact on agricultural use of surrounding areas, boosting the use index by 0.23 for areas within 50 km. Larger cities actually had smaller impacts, perhaps because land is converted to settlements and hence does not appear in the agricultural use measure.

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[10] That is, the effect of poor roads may extend only 10 to 15 kilometers; the regression tries to take account of this through a weighted average of the two available buffer categories (0-25 and 25-50 km), which are highly correlated.

[11] 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 and Puri (1999)

We tested the sensitivity of the results to several alternative specifications. The first column of Table 5 shows a traditional tobit analysis. The results are qualitatively very similar; the main difference is a diminished impact of pre-1976 clearing. There is still a 0.40 drop in the index as rainfall increases from 1,300 mm to 2,500 mm, with a leveling off thereafter.[12] Table 6 repeats the regression with an alternative specification for precipitation. The alternative has a linear term in mean precipitation, a dummy for a 'dry season' – at least two consecutive months of less than 50 mm rainfall – and an interaction between these two variables. It tells the same story as the previous regression: at low levels of precipitation, where most areas have at least two dry months (see Table 7), the index drops rapidly with increasing precipitation. Above about 2,800 mm, where most areas have no more than 1 dry month, the index continues to decline with increased precipitation, but more slowly.

Table 9 shows the original regressions reproduced for a different dependent variable: proportion of the census tract in pasture. The results are qualitatively very similar to those for all kinds of agriculture. The effect of precipitation is now even steeper; the two quadratic terms are jointly very significant, but receive low *z*-statistics because the combined effect is nearly linear.

The deterrent effect of precipitation on agriculture is quite powerful, according to these estimates. Using the coefficients of Table 5, little immediate clearing is expected on soils characterized by "low nutrient holding capacity", where precipitation exceeds 1,800 mm even in the presence of a road – unless the location is near a previous clearing or close to a small city. Clearing may occur over time in the vicinity of previous agriculture or near small cities. Even in the presence of these stimuli, clearing declines asymptotically to zero as rainfall increases.

Because the model crudely incorporates dynamics, it can be used to predict, in an indicative way, patterns of future agricultural expansion. We do so by assuming that dynamics have not changed appreciably since 1976. This is a very strong, perhaps untenable, assumption. Clearly, for instance, various government programs, including fiscal incentives, subsidized credit, and colonization programs, have been discontinued during the past decade. In addition, the drastic reduction in inflation may have removed the incentive to claim land as an inflation hedge. Nonetheless, for exploratory purposes we use the estimated coefficient for "clearing in 1976" to multiply the variable "clearing in 1987." The resultant predictions might be taken as representing predicted land use around 2006. The precise date should not be taken seriously, given our relative ignorance of dynamics; what is more important is the geographical pattern of areas predicted to be at risk. The predicted patterns in Map 15 should be compared to the predicted pattern for 1995 shown in Map 14. Despite the caveats that attach to this prediction, it is instructive because it predicts relatively little sprawl outward from the nuclei of clearing along the principal roads in western Amazonas: the predicted agroclimatic deterrent is too great. In contrast, the predictions show substantial forest loss in drier areas such as southwest Pará, and northwest Mato Grosso. It should be stressed that these predictions do not take into account the fire dynamics that have been so well described by the IPAM/WHRC (Nepstad, et al, 1999) research team, but the predicted areas of clearance overlap with areas at risk for the spread of fire. The predictions also do not allow for the effects of road construction or improvement. Both these factors might lead to greater clearing than predicted in the drier areas.

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[12] There is a slight upturn in the index after about 3000 mm, almost surely an artifact of the functional form given the few observations in this range.

Analysis of stocking rate

To examine the determinants of land value, we concentrate on the stocking ratio as an objective, easily understood proxy. The analysis proceeds in two steps:

- What determines the location of commercially oriented pasture (proxied by mean pasture size greater than five hectares)?
- Within these areas, what are the determinants of the stocking ratio?

We set this up as a sample-selection problem:

$$r = X\beta + u$$

$$y^* = Z\gamma + e$$

$$y^* > 0 \Rightarrow y = 1; \;\; y \leq 0 \Rightarrow y = 0$$

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 $y = 1$. Correlation of the disturbances allows for the possibility that areas with pasture greater than five 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. That is, we can estimate the stocking ratio equation on areas with mean pasture greater than 5 hectares without the necessity of a sample selection adjustment, and can impute the predicted values outside the sample.

Table 10 shows alternative estimates of the stocking ratio equation. The first column includes farm size and the ratio of unpaid labor to farm area as explanatory variables. Holding agroclimatic conditions constant, farm size is strongly negatively correlated with stocking rate[13]. A 10 percent increase in farm size reduces the stocking rate by about 1.6 percent; a 10 percent increase in the ratio of family labor to agricultural land increases the stocking rate by about 0.4 percent. Assuming unpaid family labor does not increase with farm size, a 50 hectare farm is predicted to have a stocking rate 65 percent higher than a 500 hectare farm.

Other things equal, location in the cerrado decreases stocking rates by 38 percent; location in Tocantins decreases stocking rates by a similar factor. Proximity to good-quality principal roads (within 25 km) boosts the stocking rate by about 10 percent; there is no statistically significant impact at greater distances, or from poor-quality principal roads. However, proximity to clearing at 1976 has a large, statistically significant effect. Areas that had been cleared by that date have stocking rates about 47 percent higher than otherwise comparable areas; the effect persists, at slightly lower magnitudes, out to 200 km from the boundary of the 1976 clearing. This is an encouraging sign that pasture use intensifies over time. But the coefficient on past clearing may also capture road and market access impacts. Location near a medium-sized city has a negligible measured effect on the stocking density, as does location near roads. Location near a large city tends to substantially reduce the stocking rate. This is surprising, given the presumed effect of urban demand on dairy farming,

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[13] Of course, farm size and labor use may themselves respond to agroclimatic and market variables. For this reason an alternative specification excludes these variables as endogenous.

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

Holding these and other factors constant, a 1,000 mm increase in precipitation decreases stocking rates by about 38 percent. Consider a 500 hectare farm in Pará with the characteristics noted in the previous example. At 1,600 mm, the predicted stocking rate is 0.38; at 2,000 mm, the stocking rate is 0.31; and at 2,300, 0.27.

The remaining columns show the results of alternative specifications. Dropping the state dummies (column 2) intensifies the impact of *cerrado* location, of higher precipitation, and of prior clearing. Dropping the farm size and labor variables (arguably endogenous) reduces the effect of precipitation, but a 1,000 mm increase still reduces stocking by a factor of 28 percent. *Cerrado* location maintains its depressing impact in this specification.

Conclusions

Findings

Principal findings are as follows:

Most agricultural land in Amazônia yields little private economic value.

Nearly 90% of agricultural land in the Amazon is either devoted to pasture or has been out of use for more than four years. About 40% of the currently-utilized pasture has a stocking ratio of less than 0.5 cattle/hectare, with a mean of about 0.3; the remainder has a mean stocking ratio of 0.95. Farm level studies suggest that most of this extensive pasture yield very low private returns to the landholder. This is consistent with data from the agricultural census showing negligible net revenue for most of the Legal Amazon. However, the costs of forest conversion to society are potentially large. Clearing is associated with large-scale runaway fires that impose substantial costs to Brazil in respiratory disease, disruption of economic activity, and damage to timber, pastures, crops, and fencing. Clearing and associated fires may trigger local climate changes; it has been suggested that in dry years, smoke from fires could inhibit rainfall, triggering prolonged regional droughts (IPAM, 2000). And clearing imposes national and global costs through loss of biodiversity and emissions of greenhouse gases.

Land in Amazônia is overwhelming concentrated in large properties.

Almost half of Amazonian farmland is located in the one percent of properties than have more than 2,000 hectares. This snapshot of current landholding patterns is consistent with remote sensing measures of deforestation, which show that 52 percent of total clearing occurs in individual patches of more than 100 hectares (INPE, 1999). This suggests that the modest private gains associated with agriculture in the Amazon accrue mostly to large landholders. There is also evidence that, other things equal, larger landholders utilize pasture at a substantially lower stocking rate than smaller ones.

Land in the very moist regions of the western Amazon has been extremely unattractive for agricultural development as currently and historically practiced.

Multivariate analysis shows 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 (such as road access) constant. Proxies for land abandonment are higher in high rainfall areas. This suggests that the returns to agriculture in these regions have been lower than in

Amazônia as a whole. At the very least, we can say that it has been more attractive to develop other areas first, even controlling for road access. Although it is possible that spatial patterns of development reflect geographically targeted development plans, the climatic story is consistent with agronomic hypotheses about the effect of high rainfall levels and short dry seasons on production. There are indications, however, that some of the high-precipitation areas might be suitable for agroforestry or some kinds of perennial crops.

Much cerrado land is also used with very low intensity.

Other things equal, stocking rates are very low in *cerrado* areas.

Land use intensifies over time.

An encouraging finding is that the frontier is not 'hollow.' In general, areas near medium sized cities and older settlements have both higher rates of overall agricultural use, higher proportions of area in active pasture, and higher stocking rates on pasture.

Discussion

These findings suggest a number of issues for discussion. Deforestation in the eastern Amazon has led overwhelmingly to the creation of low-productivity extensive pasture, and available evidence suggests that replication of this strategy in the West would be even less successful. 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 analysis of past experience sounds a strong cautionary note: we have no evidence to suggest that large-scale pasture or grain cultivation will be successful in the wetter Western regions. It implies that the agricultural opportunity cost of maintaining these areas under forest cover is very low and may easily be outweighed by extractive values or option values of preservation.

Provision of new roads in these very moist areas might have limited initial impact on clearing, because of their inherent unattractiveness for agriculture. Over the long run, as communities form along these roads, clearing would increase except in the most humid areas, fragmenting the forest and disrupting biological processes.

The analysis draws particular attention to the potential impact of road-building in drier areas. In these areas, roads will have a larger immediate effect on forest conversion and cerrado use, and are more likely to trigger a dynamic process of settlement and clearance. As shown in Nepstad et al (1999), 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.

The proximity of higher and lower value land uses in the drier areas of the Amazon raises interesting policy issues. From the viewpoints both of fire prevention and biodiversity conservation, mosaic patterns of agriculture and forest reserves may be undesirable. This pattern could increase fire susceptibility and result in fragmented habitat. Policies that restrict agriculture to suitable areas might therefore be socially preferable.

In this context, the current discussion of 'relocation' of legal reserve obligations is of interest. There has been a long-standing obligation of landowners in Brazil to maintain 20 percent of each property (higher in the Legal Amazon) in natural vegetation, as a legal forest reserve (Chomitz, 1999; Bernardes, 1999). Recent discussions, as well as policy innovations in the states of Minas Gerais and Paraná, focus on allowing landowners to achieve compliance by maintaining a forest reserve on a remote property with similar biological features. In principle, this kind of trade can greatly reduce the costs of achieving the desired aggregate forest reserve (Chomitz, 1999). However, the success of this policy depends on:

- *the attractiveness to agriculture of both the buying and selling properties.* If properties that are not attractive to conversion are allowed to sell legal reserve to properties under severe pressure for conversion, total deforestation will decrease relative to enforcement of the property-by-property rule.
- *the substitutability, for environmental purposes, of natural vegetation on the two properties.* Under what conditions would we be willing to accept conservation of one forest as compensation for loss of another? There is no easy answer. Tighter restrictions on substitutability (e.g., restricting compensation to within a microwatershed) provides a surer guarantee of representivity of biological features – but restricts the possible gains from specializing agricultural production in the most suitable areas.

The analyses presented in this paper provide a starting point for examining the implications of alternative ways to implement compensation mechanisms for the legal forest reserve.

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Table 1. Main sources of revenue for farm establishments by state

	Number of farm establish-ments	Area of farm establish-ments (000s ha)	Area of farm establish-ments (% of state)	Gross value of agricultural production (000s reais)	Ranking of gross value of production (top 4, includes only those products > 5% of total)							
					First		Second		Third		Fourth	
					Product	Percent of total	Product	Percent of total	Product	Percent of total	Product	Percent of total
Acre	23,788	3,183	2.1%	107,201	Manioc	30.6%	Cattle	12.4%	Cow's milk	8.9%	Maize	5.2%
Amapá	3,349	700	4.9%	68,872	Silviculture	51.2%	Cattle	11.7%	Manioc	9.2%	Oil palm	5.8%
Amazonas	83,289	3,323	2.1%	366,496	Manioc	48.8%	Banana	10.5%				
Maranhão	368,191	12,561	37.6%	698,163	Rice	15.8%	Cattle	14.4%	Manioc	8.1%	Cow's milk	7.9%
Mato Grosso	78,762	49,840	55.0%	1,990,221	Soybeans	36.8%	Cattle	17.5%	Sugarcane	10.2%	Maize	5.7%
Pará	206,404	22,520	18.0%	1,026,711	Manioc	15.4%	Cattle	14.5%	Logs	9.4%	Cow's milk	7.4%
Rondônia	76,956	8,890	37.2%	334,210	Cow's milk	18.3%	Coffee	16.0%	Cattle	13.4%	Beans	6.6%
Roraima	7,476	2,977	13.2%	62,084	Rice	16.8%	Cow's milk	10.6%	Manioc	6.8%	Maize	6.1%
Tocantins	44,913	16,766	60.2%	356,366	Cattle	37.9%	Rice	13.3%	Cow's milk	10.2%		
All farms	893,128	120,759	18.6%	5,010,324	Cattle	16.2%	Soybeans	15.3%	Manioc	9.2%	Cow's milk	6.9%

Notes:

1) "Cattle" and "Chicken" are values of sales plus value of slaughtered, minus purchases.
2) Silviculture is used to mean all type of tree plantations (other than fruit, coffee, and cocoa).
3) Percent is based on total value of agricultural production as given in Table 23 of the Agricultural Census.
4) The values in this table are for the entire state, not just the portion of the state within the Legal Amazon.

Table 2. Main sources of revenue for farm establishments by size of farm

Total land area of farms (hectares)	Number of farm establishments	Area of farm establishments (000s ha)	Percent in agricultural land	Gross value of agricultural production (000s reais)	Ranking of gross value of production (top 4, includes only those products > 5% of total)							
					First		Second		Third		Fourth	
					Product	Percent of total	Product	Percent of total	Product	Percent of total	Product	Percent of total
"No size given	16,873	0	NA	16,041	Babaçu	53.7%	Charcoal	15.2%	Logs	9.2%		
0 - 1	154,502	89	96.9%	145,500	Manioc	17.8%	Rice	14.2%	Babaçu	8.1%	Charcoal	5.4%
1 - 2	106,671	147	94.6%	127,784	Manioc	23.0%	Rice	17.7%	Babaçu	5.9%		
2 - 5	101,017	310	85.4%	226,266	Manioc	29.9%	Rice	9.9%	Banana	6.7%		
5 - 10	54,514	376	71.4%	167,014	Manioc	29.3%	Banana	7.7%	Chickens	5.1%		
10 - 20	64,028	867	66.2%	216,836	Manioc	27.3%	Cow's milk	6.3%	Banana	5.2%		
20 - 50	139,442	4,521	62.9%	447,840	Manioc	22.6%	Cow's milk	11.7%	Rice	7.5%	Cattle	5.5%
50 - 100	110,063	7,305	55.8%	445,456	Cow's milk	15.7%	Manioc	14.7%	Cattle	9.9%	Rice	7.5%
100 - 200	74,001	9,130	55.1%	411,641	Cow's milk	17.2%	Cattle	14.6%	Manioc	11.5%	Rice	6.3%
200 - 500	39,434	11,892	63.4%	445,454	Cattle	20.7%	Cow's milk	13.5%	Soybeans	12.1%	Rice	5.2%
500 - 1,000	14,869	10,276	64.9%	399,941	Soybeans	27.3%	Cattle	21.6%	Cow's milk	6.5%	Sugarcane	6.5%
1,000 - 2,000	8,793	12,202	65.8%	496,439	Soybeans	34.2%	Cattle	25.4%	Maize	5.4%	Sugarcane	5.1%
2,000 - 5,000	5,829	17,492	62.3%	597,268	Soybeans	34.2%	Cattle	21.9%	Sugarcane	8.3%		
5,000 - 10,000	1,843	12,701	56.2%	350,049	Soybeans	33.7%	Cattle	26.4%	Rice	6.3%		
10,000 - 100,000	1,218	26,094	45.6%	455,256	Cattle	28.1%	Soybeans	22.8%	Sugarcane	19.9%	Rice	7.6%
More than 100,000	31	7,358	17.6%	61,539	Silviculture	64.2%	Sugarcane	11.3%	Cattle	10.9%		
All farms	893,128	120,759	55.3%	5,010,324	Cattle	16.2%	Soybeans	15.3%	Manioc	9.2%	Cow's milk	6.9%

Notes:

1) "Cattle" and "Chicken" are values of sales plus value of slaughtered, minus purchases.
2) Silviculture is used to mean all type of tree plantations (other than fruit, coffee, and cocoa).
3) Percent is based on total value of agricultural production as given in Table 23 of the Agricultural Census.
4) The values in this table are for the entire state, not just the portion of the state within the Legal Amazon.

Table 3. Main sources of agricultural revenue by rainfall category

Rainfall (m)	Number of Muni-cipios	Number of farm establish-ments	Area of farm establish-ments (000s ha)	Mean size of farm establish-ments (ha)	Percent of area in farm establih-ments	Gross value of agricultural production (000s reais)	Ranking of gross value of production (top 3)					
							First		Second		Third	
							Product	Percent of total	Product	Percent of total	Product	Percent of total
All farms	***561***	***663,638***	***116,054***	***175***	***24.0%***	***3,534,820***	***Cattle***	***21.9%***	***Soybeans***	***21.7%***	***Manioc***	***12.1%***
1.4 - 1.6	14	11,731	6,935	591	64.0%	114,909	Cattle	65.6%	Sugarcane	6.8%	Maize	6.6%
1.6 - 1.8	168	112,890	39,744	352	55.0%	1,127,283	Soybeans	32.9%	Cattle	27.3%	Sugarcane	9.9%
1.8 - 2.0	129	130,414	35,243	270	35.0%	1,072,935	Soybeans	36.9%	Cattle	19.7%	Sugarcane	10.6%
2.0 - 2.2	63	121,339	17,459	144	21.0%	357,613	Cattle	28.0%	Manioc	15.0%	Rice	12.3%
2.2 - 2.4	70	101,641	8,046	79	7.0%	266,346	Manioc	38.6%	Cattle	12.9%	Bananas	8.3%
2.4 - 2.6	30	54,702	3,030	55	7.0%	163,219	Manioc	45.2%	Cattle	12.1%	Logs	10.5%
2.6 - 2.8	41	88,583	4,008	45	11.0%	262,524	Manioc	36.7%	Logs	20.4%	Cattle	7.0%
2.8 - 3.0	42	38,524	1,381	36	15.0%	149,905	Chickens	33.6%	Manioc	27.0%	Bananas	6.8%
3.0 - 3.2	2	1,061	197	185	3.0%	4,158	Manioc	46.5%	Bananas	25.5%	Cattle	16.1%
3.2 - 3.4	2	2,753	11	4	0.0%	15,927	Manioc	71.3%	Bananas	10.8%	Pineapples	9.1%

Notes:

1) "Cattle" and "Chicken" are values of sales plus value of slaughtered, minus purchases.

2) The values in this table are for municipios in the Legal Amazon of Brazil with centroids west of 45W.

3) Percent of area in farms is based on sector data, and is therefore on approximate for municipios.

4) Percent is based on total value of agricultural production as available at the municipio level. This excluded milk and various commodities produced in small percentages. The value of agricultural production east of 45W is approximately 219m reais. The value of milk production is approximately 347m reais. The small percentage commodities and other exclusions total approximately 1b reais.

Table 4. Overview of study area

		Annual rainfall category (range is in meters)												Sub-total	East of 45W	Total
		1.2 - 1.4	1.4 - 1.6	1.6 - 1.8	1.8 - 2.0	2.0 - 2.2	2.2 - 2.4	2.4 - 2.6	2.6 - 2.8	2.8 - 3.0	3.0 - 3.2	3.2 - 3.4	3.4 - 3.6			
		All census tracts														
	Number of census tracts	4	125	1,274	1,330	881	1,033	405	596	340	60	35	11	6,094	682	6,776
	Total area (000s hectares)	1,620	8,538	73,746	101,244	81,427	113,681	46,744	29,460	10,998	8,336	7,392	3,314	486,499	6,250	492,749
	Protected areas (% of total area)	8.5%	7.5%	14.4%	29.6%	29.7%	20.4%	21.7%	21.8%	8.0%	45.7%	81.2%	84.1%	24.4%	0.0%	24.1%
	Number of farms	97	11,116	106,688	140,321	122,414	105,694	53,629	81,307	37,869	4,410	1,758	378	665,681	127,069	792,750
	Establishments (% of total area)	41.4%	63.8%	55.0%	35.5%	20.8%	7.1%	7.1%	10.8%	15.1%	3.5%	0.1%	0.0%	23.9%	41.2%	24.1%
% of establishment area	**Native forest on farmland**	22.5%	25.2%	26.4%	46.7%	63.5%	62.6%	56.1%	48.2%	29.1%	22.4%	16.5%	2.0%	42.0%	18.8%	41.5%
	Agricultural land	64.6%	67.8%	69.0%	50.9%	34.6%	35.3%	40.9%	47.6%	67.2%	69.8%	75.1%	84.7%	54.5%	77.7%	55.0%
	Annual crops	0.2%	1.5%	4.0%	5.2%	1.9%	2.5%	3.3%	4.5%	3.5%	1.7%	50.1%	54.3%	3.8%	7.5%	3.9%
	Perennials	0.0%	0.9%	0.3%	0.6%	1.2%	1.8%	1.1%	3.2%	2.6%	1.6%	19.9%	29.1%	0.8%	0.8%	0.8%
	Total pasture	63.4%	60.7%	56.6%	39.5%	27.2%	22.0%	25.4%	18.1%	41.0%	63.2%	1.9%	0.2%	42.7%	41.4%	42.6%
	Tree plantations	0.0%	0.0%	0.1%	0.2%	0.2%	1.8%	0.7%	0.2%	0.1%	0.0%	0.0%	0.0%	0.3%	0.1%	0.3%
	Fallow	0.6%	1.2%	1.9%	1.5%	1.4%	1.9%	2.3%	5.7%	3.4%	0.2%	1.6%	0.0%	1.8%	11.5%	2.0%
	Productive but unutilized	0.5%	3.5%	6.2%	3.9%	2.6%	5.4%	8.1%	15.8%	16.5%	3.1%	1.6%	1.1%	5.2%	16.3%	5.4%
		Census tracts with a portion closer than 25 km from a principal road														
	Number of census tracts	0	100	859	707	489	451	89	115	171	15	3	1	3,000	482	3,482
	Total area (000s hectares)	0	5,818	48,046	50,376	39,807	50,514	14,361	5,196	2,608	3,564	910	367	221,567	4,762	226,328
	Protected areas (% of total area)	NA	7.6%	13.7%	23.2%	26.1%	16.2%	17.4%	3.1%	12.8%	62.4%	81.7%	98.9%	19.7%	0.0%	19.3%
	Number of farms	0	10,112	76,488	78,663	83,240	53,368	14,225	19,120	21,050	801	94	130	357,291	90,710	448,001
	Establishments (% of total area)	NA	64.2%	58.9%	43.4%	18.7%	10.4%	10.0%	17.0%	32.7%	1.5%	0.0%	0.1%	31.5%	44.8%	31.8%
% of establishment area	**Native forest on farmland**	NA	24.9%	26.3%	46.5%	53.2%	62.5%	43.3%	28.1%	34.1%	43.3%	0.4%	0.5%	38.6%	18.9%	38.0%
	Agricultural land	NA	68.3%	69.2%	51.1%	44.9%	35.3%	53.8%	67.8%	61.5%	55.2%	92.7%	85.0%	57.9%	77.7%	58.5%
	Annual crops	NA	2.1%	4.7%	5.9%	3.0%	2.0%	3.1%	5.5%	3.7%	2.8%	67.9%	50.1%	4.5%	7.0%	4.6%
	Perennials	NA	1.2%	0.3%	0.7%	1.7%	1.3%	0.8%	2.2%	3.4%	1.7%	22.6%	34.4%	0.8%	0.6%	0.8%
	Total pasture	NA	59.2%	56.0%	39.0%	33.6%	23.2%	38.5%	29.7%	31.3%	48.4%	0.0%	0.5%	45.0%	42.6%	44.9%
	Tree plantations	NA	0.1%	0.2%	0.2%	0.4%	2.7%	0.7%	0.3%	0.2%	0.0%	0.0%	0.0%	0.4%	0.1%	0.4%
	Fallow	NA	1.5%	1.9%	1.6%	2.3%	1.4%	2.1%	7.3%	4.3%	0.0%	0.0%	0.0%	1.9%	11.6%	2.2%
	Productive but unutilized	NA	4.3%	6.1%	3.7%	3.9%	4.7%	8.6%	22.8%	18.5%	2.3%	2.2%	0.0%	5.3%	15.7%	5.7%
		Census tracts with no portion closer than 25 km from a principal road														
	Number of census tracts	4	25	415	623	392	582	316	481	169	45	32	10	3,094	200	3,294
	Total area (000s hectares)	1,620	2,720	25,700	50,868	41,620	63,167	32,383	24,264	8,389	4,772	6,482	2,948	264,932	1,488	266,420
	Protected areas (% of total area)	8.5%	7.4%	15.8%	35.9%	33.1%	23.8%	23.6%	25.8%	6.5%	33.3%	81.2%	82.2%	28.4%	0.0%	28.2%
	Number of farms	97	1,004	30,200	61,658	39,174	52,326	39,404	62,187	16,819	3,609	1,664	248	308,390	36,359	344,749
	Establishments (% of total area)	41.4%	62.9%	47.7%	27.6%	22.8%	4.6%	5.9%	9.4%	9.7%	5.0%	0.1%	0.0%	17.5%	29.8%	17.5%
% of establishment area	**Native forest on farmland**	22.5%	25.9%	26.7%	46.9%	71.6%	62.7%	65.6%	55.9%	23.7%	17.7%	17.3%	3.0%	47.1%	18.4%	46.8%
	Agricultural land	64.6%	66.8%	68.5%	50.5%	26.4%	35.3%	31.3%	39.8%	73.3%	73.1%	74.2%	84.4%	49.4%	77.7%	49.7%
	Annual crops	0.2%	0.3%	2.3%	4.2%	1.1%	3.3%	3.5%	4.1%	3.3%	1.5%	49.2%	57.0%	2.8%	10.1%	2.8%
	Perennials	0.0%	0.1%	0.2%	0.6%	0.8%	2.6%	1.3%	3.6%	1.7%	1.6%	19.8%	25.7%	0.8%	1.7%	0.8%
	Total pasture	63.4%	63.9%	57.9%	40.1%	22.2%	20.0%	15.5%	13.7%	51.2%	66.5%	2.0%	0.0%	39.1%	35.6%	39.1%
	Tree plantations	0.0%	0.0%	0.1%	0.2%	0.1%	0.1%	0.8%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%
	Fallow	0.6%	0.6%	1.8%	1.3%	0.7%	2.7%	2.4%	5.1%	2.6%	0.3%	1.7%	0.0%	1.6%	11.4%	1.7%
	Productive but unutilized	0.5%	1.9%	6.2%	4.2%	1.6%	6.7%	7.7%	13.1%	14.5%	3.3%	1.6%	1.7%	5.0%	18.9%	5.1%

Note:establishment area=agricultural area+native forest+ unutilizable area(not shown)
Agricultural land= annuals+perennials+total pasture+tree plantations+fallow+productive nonutilized

Table 5. Regressions on proportion of census tract in agriculture land

Variable	Param	t-stat	Param	t-stat	Param	t-stat
State (omitted Rondonia)						
Acre	-0.1323	-5.73	-0.1804	-7.57	-0.1870	-4.68
Amazonas	-0.0190	-1.13	-0.0927	-6.19	-0.1016	-4.35
Roraima	0.0179	0.57	0.190	3.48	-0.0764	-3.17
Para	0.0031	0.21	0.0242	1.47	0.0188	0.95
Amapa	-0.0633	-1.87	-0.0915	-3.26	-0.1849	-5.32
Tocantins	0.1213	6.86	0.1251	5.25	0.1543	3.98
Maranhao	-0.0074	-0.44	-0.0365	-2.19	-0.0252	-0.68
Mato Grosso	0.0589	3.89	0.0614	2.86	0.0950	3.16
Distance to land cleared by 1976, proportion of sector in (omitted > 200 km)						
Cleared by 1976	0.2378	9.96	0.4386	11.52	NA	NA
1 - 50 km buffer	0.0973	4.50	0.2759	8.82	NA	NA
50 - 100 km buffer	0.0224	1.01	0.2000	5.78	NA	NA
100 - 200 km buffer	0.0085	0.39	0.1869	5.63	NA	NA
Annual rainfall at sector centroid (mm)						
Annual	-1.34E-03	-11.17	-7.87E-04	-3.07	-1.76E-03	-8.26
Annual, squared	2.64E-07	10.41	1.23E-07	2.19	3.52E-07	7.79
Buffers around principal roads (omitted > 50 km)						
Poor quality, 0 - 25 km	0.0668	4.41	0.0602	3.54	0.0920	3.38
Poor quality, 25 - 50 km	0.0122	0.62	-0.0773	-4.48	-0.0722	-2.21
Good quality, 0 - 25 km	0.0727	6.91	0.0766	5.92	0.0962	4.61
Good quality, 25 - 50 km	0.0668	5.58	0.0679	5.01	0.0974	4.31
Buffers around principal rivers (omitted is >50 km)						
0 - 25 km	-0.0755	-5.13	-0.1200	-8.71	-0.1245	-4.71
25 - 50 km	-0.0740	-4.07	-0.0894	-5.69	-0.0804	-2.68
Protected areas of any type,	-0.2219	-15.51	-0.2877	-10.67	-0.3174	-6.59
Primary limiting factors of soils (omitted "low organic matter")						
Seasonal excess water	0.2519	2.69	0.2361	1.31	0.3344	1.67
Minor root restricting layer	-0.0693	-2.66	-0.0942	-3.46	-0.0617	-1.70
Impeded drainage	-0.0801	-3.21	-0.0914	-3.39	-0.1103	-4.09
Seasonal moisture stress	-0.0634	-2.75	-0.0694	-2.61	-0.0680	-2.77
High aluminum	-0.0101	-0.28	-0.0357	-0.64	-0.0558	-0.93
Excessive nutrient leaching	0.0173	0.59	0.0073	0.21	0.0156	0.38
Low nutrient holding capacity	-0.0931	-4.01	-0.0949	-3.94	-0.1252	-5.55
High P, N, & organic retention	-0.0940	-2.32	-0.1285	-2.09	-0.0718	-1.09
Low water holding capacity	-0.0617	-2.34	-0.0490	-1.43	-0.0564	-1.34
Salinity or alkalinity	-0.1050	-3.23	-0.1341	-3.70	-0.1960	-5.10
Shallow soils	-0.1631	-3.99	-0.1670	-2.22	-0.1947	-3.44
Buffers around cities with populations of 100,000 or more (omitted > 250 km)						
0 - 50 km	-0.1610	-8.34	-0.1492	-6.60	-0.1210	-4.73
50 - 100 km	-0.0381	-2.65	-0.0435	-2.22	-0.0065	-0.35
100 - 250 km	-0.0027	-0.28	-0.0166	-1.10	-0.0054	-0.30
Buffers around cities with populations of 25,000 or more (omitted > 250 km)						
0 - 50 km	0.1628	7.73	0.2279	6.66	0.2970	8.04
50 - 100 km	0.0850	4.11	0.1347	4.01	0.1751	4.93
100 - 250 km	-0.0006	-0.03	0.0346	1.05	0.0491	1.17
Vegetation classes (omitted "forest")						
Pioneer	0.0177	0.77	0.0100	0.52	0.0279	0.85
Cerrado	0.0206	1.37	0.0396	1.57	-0.0381	-1.09
Cerrado-forest	-0.0321	-1.84	-0.0550	-2.42	-0.0720	-1.94
Constant	1.8025	12.75	1.0470	3.59	2.2635	9.38

Notes:

1) Bootstrap t-statistics are based on 50 repetitions.

2) The first iterated quantile converged to a pattern that gave the same parameter estimates every iteration, starting at iteration 15.

3) The second iterated quantile converged to a pattern that repeated identical parameter estimates every 5 iterations, starting at iteration 14 (i.e, 14 and 19 had the same results, 15 and 20, etc.). Following Deaton (p. 90), out of the 5 possible choices, we chose the iteration with the highest criterion, which was iteration 18.

4) We dropped low structural stability, campinarana, and forest-campinarana due to the number of non-zero values, which was causing some iterations of the quantile regression to not converge.

5) Regressions were on those sectors located west of 45 degrees west. Excluded were those with computed areas less than 400 hectares, and those with ten or more sectors merged together (an indicator of being an urban area).

Table 6. Regression on proportion of census tract in agricultural land, with dry months as categorical variable

Variable	Param	t-stat
State (omitted is Rondonia)		
Acre	-0.1957	-7.62
Amazonas	-0.0880	-4.03
Roraima	0.1820	3.03
Para	0.0314	1.52
Amapa	-0.2375	-0.85
Tocantins	0.1302	5.83
Maranhao	-0.0392	-1.70
Mato Grosso	0.0575	2.72
Distance to land cleared by 1976, proportion of sector in (omitted is > 200 km)		
Cleared by 1976	0.4463	14.88
1 - 50 km buffer	0.2688	9.22
50 - 100 km buffer	0.1827	5.91
100 - 200 km buffer	0.1738	5.04
Rainfall at centroid of census tract		
At least 2 consecutive dry months (1 if yes, 0 if no)	0.4007	3.85
Annual (mm)	-1.31E-04	-2.81
Annual * At least 2 consecutive dry months	-1.62E-04	-3.58
Buffers around principal roads, proportion of sector in (omitted is > 50 km)		
Poor quality, 0 - 25 km	0.0759	3.44
Poor quality, 25 - 50 km	-0.0444	-1.43
Good quality, 0 - 25 km	0.0621	3.86
Good quality, 25 - 50 km	0.0602	3.63
Buffers around principal rivers, proportion of sector in (omitted is > 50 km)		
0 - 25 km	-0.1333	-7.70
25 - 50 km	-0.0749	-3.08
Protected areas of any type, proportion of sector in	-0.3062	-3.11
Primary limiting factors of soils, proportion of sector in (omitted is "low organic matter")		
Seasonal excess water	0.2671	1.16
Minor root restricting layer	-0.0968	-2.49
Impeded drainage	-0.0932	-2.92
Seasonal moisture stress	-0.0744	-2.80
High aluminum	-0.0311	-0.56
Excessive nutrient leaching	-0.0059	-0.19
Low nutrient holding capacity	-0.0971	-3.37
High P, N, & organic retention	-0.1260	-2.30
Low water holding capacity	-0.0570	-1.80
Salinity or alkalinity	-0.1241	-3.12
Shallow soils	-0.1720	-2.74
Buffers around cities with populations of 100,000 or more, proportion of sector in (omitted is > 250 km)		
0 - 50 km	-0.1550	-6.52
50 - 100 km	-0.0488	-2.24
100 - 250 km	-0.0074	-0.58
Buffers around cities with populations of 25,000 or more, proportion of sector in (omitted is > 250 km)		
0 - 50 km	0.2425	3.09
50 - 100 km	0.1451	1.72
100 - 250 km	0.0459	0.50
Vegetation classes, proportion of sector in (omitted is "forest")		
Pioneer	0.0354	1.55
Cerrado	0.0484	1.95
Cerrado-forest	-0.0501	-1.86
Constant	0.1631	2.09

Notes:

1) Bootstrap t-statistics are based on 50 repetitions.

2) The iterated quantile converged at iteration 21.

3) We dropped low structural stability, campinarana, and forest-campinarana due to the number of non-zero values, which was causing some iterations of the quantile regression to not converge.

4) Regressions were on those sectors located west of 45 degrees west. Excluded were those with computed areas less than 400 hectares, and those with ten or more sectors merged together (an indicator of being an urban area).

Table 7. Count of census tracts by rainfall and consecutive dry months

		All	
		1 or less	2 to 5
Rainfall (m)	1.2 - 1.4	0	4
	1.4 - 1.6	1	124
	1.6 - 1.8	15	1,259
	1.8 - 2.0	143	1,187
	2.0 - 2.2	371	510
	2.2 - 2.4	760	273
	2.4 - 2.6	341	64
	2.6 - 2.8	437	159
	2.8 - 3.0	303	37
	3.0 - 3.2	52	8
	3.2 - 3.4	35	0
	3.4 - 3.6	11	0
	Total	2,469	3,625
	All census tracts	6,094	

Table 8. Summary of variables used in census tract/ agricultural land regressions

Variable	Number of observations	Mean	Std. Dev.	Min	Max
Proportion of sector converted for agriculture	5933	0.3097	0.5662	0	21.0805
Proportion of sector in agricultural establishments	5933	0.2243	0.4829	0	20.9654
State					
Rondonia	5933	0.1360	0.3428	0	1
Acre	5933	0.0329	0.1783	0	1
Amazonas	5933	0.1643	0.3706	0	1
Roraima	5933	0.0300	0.1706	0	1
Para	5933	0.2660	0.4419	0	1
Amapa	5933	0.0138	0.1168	0	1
Tocantins	5933	0.0971	0.2961	0	1
Maranhao	5933	0.1038	0.3051	0	1
Mato Grosso	5933	0.1561	0.3630	0	1
Distance to land cleared by 1976, proportion of sector in (omitted is > 200 km)					
Cleared by 1976	5933	0.1435	0.3075	0	1
1 - 50 km buffer	5933	0.4086	0.4369	0	1
50 - 100 km buffer	5933	0.1914	0.3461	0	1
100 - 200 km buffer	5933	0.1419	0.3214	0	1
Rainfall					
Annual (mm)	5933	2,140	395	1,331	3,513
Annual, squared	5933	4,735,192	1,798,265	1,771,561	12,300,000
# of consecutive months < 50mm	5933	1.8716	1.4974	0	5
# of months squared	5933	5.7445	5.3462	0	25
1, if # of consecutive months >= 2; 0 otherwise	5933	0.5951	0.4909	0	1
Buffers around principal roads, proportion of sector in					
Poor quality, 0 - 25 km	5933	0.0843	0.2520	0	1
Poor quality, 25 - 50 km	5933	0.0593	0.1823	0	1
Good quality, 0 - 25 km	5933	0.2698	0.4086	0	1
Good quality, 25 - 50 km	5933	0.1938	0.3263	0	1
Buffers around principal rivers, proportion of sector in					
0 - 25 km	5933	0.1958	0.3777	0	1
25 - 50 km	5933	0.0738	0.2151	0	1
Protected areas of any type, proportion of sector in	5933	0.1236	0.2828	0	1
Primary limiting factors of soils, proportion of sector in					
Low organic matter	5933	0.0381	0.1693	0	1
Seasonal excess water	5933	0.0025	0.0378	0	1
Minor root restricting layer	5933	0.0747	0.2291	0	1
Low structural stability	5933	0.0001	0.0072	0	0.5560
Impeded drainage	5933	0.0931	0.2629	0	1
Seasonal moisture stress	5933	0.3124	0.4175	0	1
High aluminum	5933	0.0190	0.1202	0	1
Excessive nutrient leaching	5933	0.0468	0.1875	0	1
Low nutrient holding capacity	5933	0.2631	0.4014	0	1
High P, N, & organic retention	5933	0.0161	0.1061	0	1
Low water holding capacity	5933	0.0869	0.2551	0	1
Salinity or alkalinity	5933	0.0275	0.1544	0	1
Shallow soils	5933	0.0199	0.1074	0	1
Buffers around cities with populations of 100,000 or more, proportion of sector in					
0 - 50 km	5933	0.0553	0.2165	0	1
50 - 100 km	5933	0.1137	0.2948	0	1
100 - 250 km	5933	0.3868	0.4691	0	1
Buffers around cities with populations of 25,000 or more, proportion of sector in					
0 - 50 km	5933	0.2631	0.4163	0	1
50 - 100 km	5933	0.3202	0.4199	0	1
100 - 250 km	5933	0.3128	0.4320	0	1
Vegetation classes, proportion of sector in					
Campinarana	5933	0.0033	0.0408	0	1
Forest	5933	0.6724	0.4374	0	1.0004
Forest-campinarana	5933	0.0139	0.1031	0	1
Pioneer	5933	0.0481	0.1906	0	1
Cerrado	5933	0.1834	0.3598	0	1.0001
Cerrado-forest	5933	0.0780	0.2198	0	1

Table 9. Regressions on proportion of pasture in census tract

	Tobit		Iterated Quantile		Iterated Quantile	
Variable	Param	t-stat	Param	t-stat	Param	t-stat
State (omitted Rondonia)						
Acre	-0.1237	-5.84	-0.1544	-6.37	-0.1330	-2.76
Amazonas	-0.0381	-2.42	-0.2444	-8.00	-0.0609	-3.26
Roraima	0.0709	2.39	0.2072	5.31	-0.0606	-2.19
Para	-0.0120	-0.89	0.0131	0.81	0.0158	0.53
Amapa	0.0000	0.00	-0.2045	-1.99	-0.1160	-1.88
Tocantins	0.1227	7.58	0.1374	6.33	0.1613	4.54
Maranhao	-0.0278	-1.80	-0.0733	-3.41	-0.0697	-2.86
Mato Grosso	0.0807	5.82	0.0769	4.19	0.1182	7.42
Land cleared by 1976, proportion of sector in (omitted > 200 km)						
0 - 1 km	0.1781	7.87	0.4199	13.23	NA	NA
1 - 50 km	0.1260	6.10	0.3127	13.27	NA	NA
50 - 100 km	0.0722	3.42	0.2379	8.57	NA	NA
100 - 200 km	0.0511	2.40	0.2215	8.43	NA	NA
Annual rainfall at sector centroid (mm)						
Annual	-1.22E-03	-10.26	-6.27E-04	-2.81	-1.04E-03	-1.87
Annual, squared	2.20E-07	8.59	6.51E-08	1.32	1.62E-07	1.40
Buffers around principal roads (omitted > 50 km)						
Poor quality, 0 - 25 km	0.0743	5.29	0.0477	2.64	0.0465	1.72
Poor quality, 25 - 50 km	0.0524	2.87	-0.0188	-0.76	-0.0274	-1.07
Good quality, 0 - 25 km	0.0674	6.99	0.0671	5.05	0.0891	7.35
Good quality, 25 - 50 km	0.0439	3.99	0.0355	3.01	0.0694	2.90
Buffers around principal rivers (omitted is 50 km)						
0 - 25 km	-0.0564	-4.08	-0.1253	-6.43	-0.0928	-4.19
25 - 50 km	-0.0708	-4.13	-0.1057	-7.48	-0.0647	-1.40
Protected areas of any type,	-0.2281	-16.35	-0.2214	-8.30	-0.2684	-7.55
Primary limiting factors of soils (omitted "low organic matter")						
Minor root restricting layer	-0.0654	-2.79	-0.0948	-3.42	-0.0629	-1.31
Impeded drainage	-0.1292	-5.63	-0.1273	-4.91	-0.1470	-3.46
Seasonal moisture stress	-0.0964	-4.71	-0.0822	-4.08	-0.0932	-1.90
High aluminum	0.0142	0.44	0.0133	0.23	-0.0192	-0.45
Excessive nutrient leaching	0.0032	0.12	0.0139	0.47	-0.0161	-0.24
Low nutrient holding capacity	-0.1083	-5.18	-0.0519	-2.55	-0.1299	-4.98
High P, N, & organic retention	-0.1784	-4.89	-0.2232	-5.26	-0.1824	-2.12
Low water holding capacity	-0.0794	-3.36	-0.0466	-1.74	-0.0530	-1.04
Salinity or alkalinity	-0.0872	-2.91	-0.2002	-5.92	-0.2284	-8.12
Shallow soils	-0.1759	-4.57	-0.1293	-3.02	-0.1513	-2.19
Buffers around cities with populations of 100,000 or more (omitted > 250 km)						
0 - 50 km	-0.1559	-8.79	-0.1843	-5.63	-0.1683	-3.74
50 - 100 km	-0.0327	-2.46	-0.0462	-2.61	-0.0301	-0.55
100 - 250 km	0.0049	0.55	-0.0128	-0.91	-0.0037	-0.13
Buffers around cities with populations of 25,000 or more (omitted > 250 km)						
0 - 50 km	0.1266	6.44	0.1710	5.80	0.2192	4.03
50 - 100 km	0.0610	3.16	0.1006	3.71	0.1131	2.51
100 - 250 km	-0.0210	-1.15	-0.0066	-0.25	-0.0143	-0.34
Vegetation classes (omitted "forest")						
Pioneer	0.0258	1.20	0.0510	1.70	0.0429	1.81
Cerrado	-0.0169	-1.23	-0.0008	-0.03	-0.0679	-1.24
Cerrado-forest	-0.0392	-2.45	-0.0748	-3.31	-0.0942	-1.83
Constant	1.6929	12.37	0.9003	3.66	1.5994	2.67

Notes:

1) Bootstrap t-statistics are based on 50 repetitions.
2) The first iterated quantile did not completely converge in 40 iterations.
3) The second iterated quantile converged after 26 iterations.
4) We dropped low structural stability and seasonal excess water as soil limiting factors, and campinarana and forest-campinarana as vegetation types, due to the number of non-zero values, which was causing some iterations of the quantile regression to not converge.
5) Regressions were on those sectors located west of 45 degrees west. Excluded were those with computed areas less than 400 hectares, and those with ten or more sectors merged together (an indicator of being an urban area).

Table 10. Regressions on natural log of stocking density (cattle per total pasture area)

Variable	Param	t-stat	Param	t-stat	Param	t-stat
State (omitted is Rondonia)						
Acre	0.0401	0.55			0.1493	1.94
Amazonas	0.0413	0.69			0.1969	3.10
Roraima	-0.6718	-5.73			-0.7628	-6.14
Para	-0.3319	-7.12			-0.3242	-6.56
Amapa	-1.2828	-11.77			-1.3467	-11.65
Tocantins	-0.4717	-8.72			-0.5085	-9.01
Maranhao	-0.4465	-8.21			-0.2446	-4.32
Mato Grosso	-0.0067	-0.14			-0.2058	-4.22
Distance to land cleared by 1976, proportion of sector in (omitted is > 200 km)						
Cleared by 1976	0.3866	4.30	0.5901	8.44	0.5500	5.82
1 - 50 km buffer	0.2994	3.63	0.5821	10.00	0.3597	4.11
50 - 100 km buffer	0.2530	3.02	0.4752	7.66	0.3174	3.57
100 - 200 km buffer	0.3274	3.79	0.5054	7.64	0.3901	4.25
Ln(labor / ha of cleared land)	0.0437	2.48	0.0827	4.69		
Ln(mean farm establishment size)	-0.1685	-9.36	-0.1235	-6.81		
Annual rainfall (mm)	-4.93E-04	-8.77	-6.51E-04	-11.89	-3.29E-04	-5.55
Buffers around principal roads, proportion of sector in (omitted is > 50 km)						
Poor quality, 0 - 25 km	0.0394	0.81	-0.0253	-0.54	0.0131	0.26
Poor quality, 25 - 50 km	0.0510	0.80	-0.0412	-0.64	0.0446	0.66
Good quality, 0 - 25 km	0.0970	2.97	0.0734	2.22	0.0984	2.84
Good quality, 25 - 50 km	0.0191	0.50	-0.0175	-0.45	0.0337	0.84
Buffers around principal rivers, proportion of sector in (omitted is > 50 km)						
0 - 25 km	0.0541	1.06	0.0544	1.10	0.1475	2.74
25 - 50 km	0.1442	2.32	0.1579	2.61	0.1476	2.24
Primary limiting factors of soils, proportion of sector in (omitted "low organic matter")						
Seasonal excess water	-0.4579	-1.76	-0.2063	-0.77	-0.5568	-2.02
Minor root restricting layer	-0.2113	-2.49	-0.2516	-2.93	-0.3059	-3.40
Impeded drainage	-0.2666	-3.11	-0.1406	-1.60	-0.1751	-1.93
Seasonal moisture stress	0.0417	0.58	0.0078	0.11	0.0210	0.27
High aluminum	0.2965	2.71	-0.0315	-0.28	0.1319	1.14
Excessive nutrient leaching	0.0989	1.09	0.2316	2.59	0.0875	0.91
Low nutrient holding capacity	0.0911	1.22	0.1009	1.35	0.1017	1.29
High P, N, & organic retention	0.2092	1.66	0.4444	3.51	-0.0475	-0.36
Low water holding capacity	-0.0963	-1.18	-0.1363	-1.63	-0.1162	-1.34
Salinity or alkalinity	-0.0696	-0.65	-0.0570	-0.52	-0.1164	-1.02
Shallow soils	0.0060	0.05	-0.0247	-0.18	-0.0454	-0.32
Buffers around cities with populations of 100,000 or more, proportion of sector in (omitted is > 250 km)						
0 - 50 km	-0.3494	-5.77	-0.4202	-6.90	-0.3299	-5.13
50 - 100 km	-0.1235	-2.65	-0.2525	-5.60	-0.1371	-2.77
100 - 250 km	-0.0493	-1.60	-0.1240	-4.24	-0.0266	-0.81
Buffers around cities with populations of 25,000 or more, proportion of sector in (omitted is > 250 km)						
0 - 50 km	0.0681	0.92	0.0101	0.14	0.0916	1.17
50 - 100 km	-0.0267	-0.37	-0.1265	-1.79	-0.0444	-0.58
100 - 250 km	-0.1565	-2.21	-0.2647	-3.82	-0.2454	-3.26
Vegetation classes, proportion of sector in (omitted is "forest")						
Pioneer	0.0256	0.32	-0.1380	-1.66	0.0585	0.68
Cerrado	-0.4810	-10.90	-0.6708	-16.12	-0.5943	-12.85
Cerrado-forest	-0.1436	-2.70	-0.1846	-3.40	-0.1860	-3.30
Constant	1.8409	10.61	1.8456	11.61	0.4879	2.84

Notes:

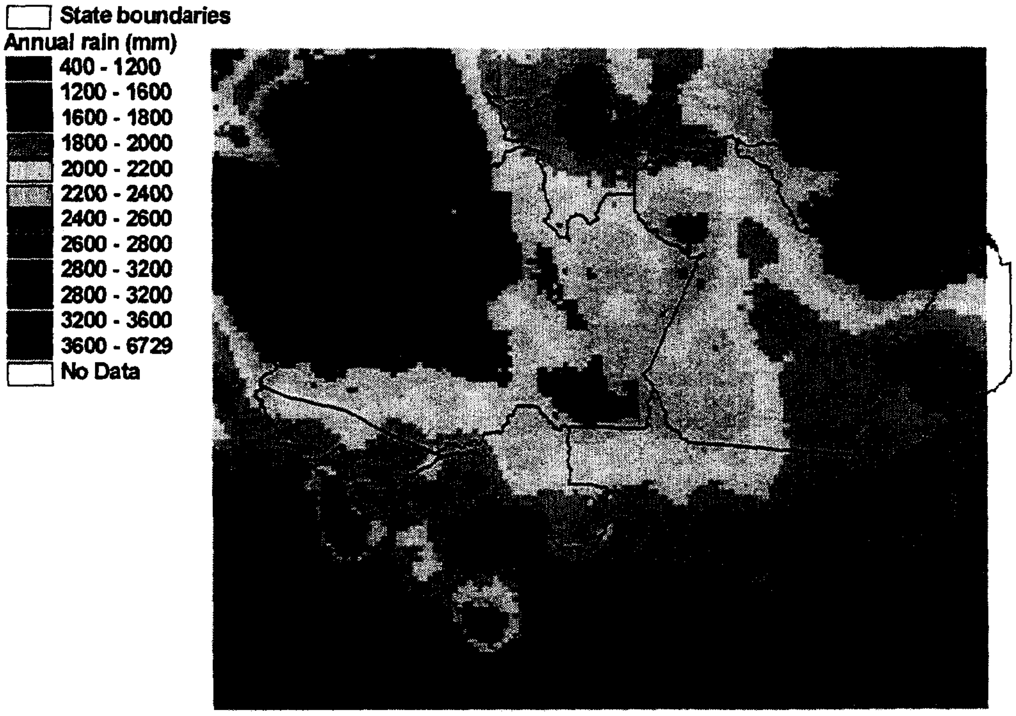
1) We dropped low structural stability, campinarana, and forest-campinarana due to the number of non-zero values.

2) Regressions were on those census tracts west of 45 degrees W. We excluded census tracts with less than 400 hectares total, and those with 10 or more sectors merged together (indicator of being an urban area).

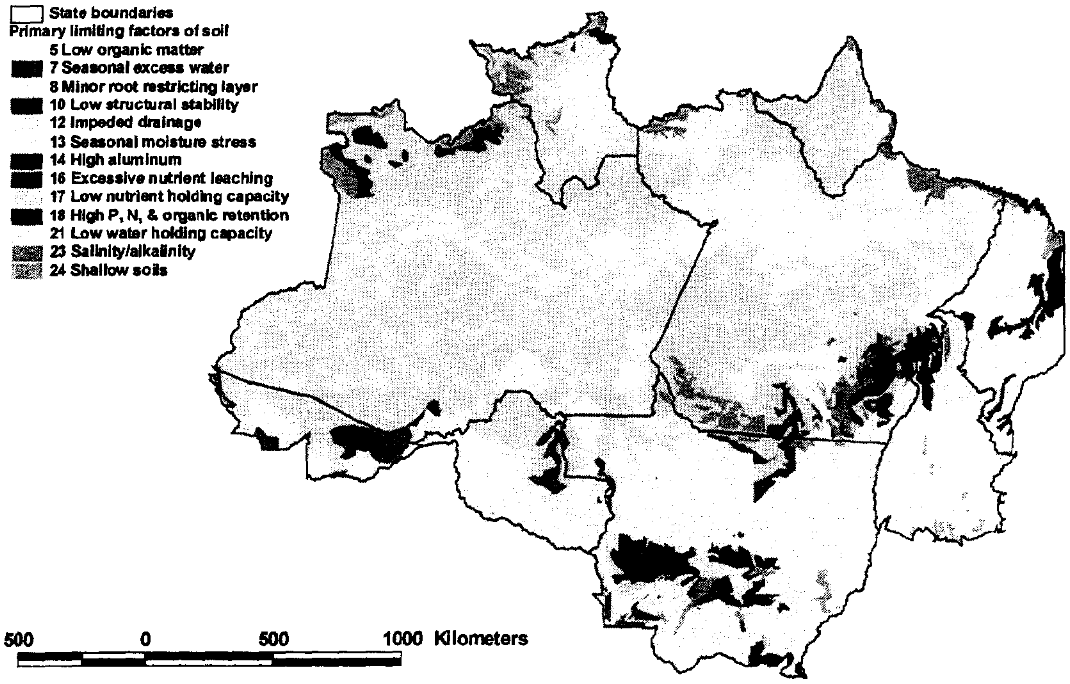
Table 11. Summary of variables used in stocking density regression

Variable	Number of observations	Mean	Std. Dev.	Min	Max
Natural log of cattle per hectare of pasture)	4407	-0.2476	0.8938	-7.3620	2.2765
Cattle per hectare of pasture	4407	1.0582	0.8561	0.0006	9.7426
Natural log of adult unpaid labor on farm	4407	-3.4501	1.8019	-11.2243	2.6589
Adult unpaid labor on farm	4407	0.1168	0.3741	0.0000	14.2806
Natural log of mean farm size	4407	5.0037	1.6552	0.1764	12.7827
Mean farm size	4407	956	7,157	1.1929	356,000
State					
Rondonia	4407	0.1536	0.3606	0	1
Acre	4407	0.0372	0.1893	0	1
Amazonas	4407	0.0917	0.2886	0	1
Roraima	4407	0.0254	0.1574	0	1
Para	4407	0.2532	0.4349	0	1
Amapa	4407	0.0134	0.1149	0	1
Tocantins	4407	0.1246	0.3303	0	1
Maranhao	4407	0.1135	0.3172	0	1
Mato Grosso	4407	0.1874	0.3903	0	1
Distance to land cleared by 1976, proportion of sector in (omitted is > 200 km)					
Cleared by 1976	4407	0.1538	0.3130	0	1
1 - 50 km buffer	4407	0.4633	0.4391	0	1
50 - 100 km buffer	4407	0.1987	0.3522	0	1
100 - 200 km buffer	4407	0.1259	0.3077	0	1
Rainfall					
Annual (mm)	4407	2,059	366	1,372	3,372
Annual, squared	4407	4,375,412	1,628,559	1,882,384	11,400,000
Buffers around principal roads, proportion of sector in					
Poor quality, 0 - 25 km	4407	0.0925	0.2634	0	1
Poor quality, 25 - 50 km	4407	0.0616	0.1864	0	1
Good quality, 0 - 25 km	4407	0.3327	0.4303	0	1
Good quality, 25 - 50 km	4407	0.2217	0.3371	0	1
Buffers around principal rivers, proportion of sector in					
0 - 25 km	4407	0.1562	0.3455	0	1.0001
25 - 50 km	4407	0.0692	0.2128	0	1.0001
Primary limiting factors of soils, proportion of sector in					
Low organic matter	4407	0.0444	0.1811	0	1
Seasonal excess water	4407	0.0034	0.0439	0	1
Minor root restricting layer	4407	0.0703	0.2231	0	1
Low structural stability	4407	0.0001	0.0084	0	0.5560
Impeded drainage	4407	0.0574	0.2070	0	1
Seasonal moisture stress	4407	0.3719	0.4332	0	1
High aluminum	4407	0.0234	0.1326	0	1
Excessive nutrient leaching	4407	0.0557	0.2058	0	1
Low nutrient holding capacity	4407	0.2083	0.3702	0	1
High P, N, & organic retention	4407	0.0181	0.1105	0	1
Low water holding capacity	4407	0.1057	0.2785	0	1
Salinity or alkalinity	4407	0.0243	0.1430	0	1
Shallow soils	4407	0.0170	0.0975	0	1
Buffers around cities with populations of 100,000 or more, proportion of sector in					
0 - 50 km	4407	0.0617	0.2262	0	1
50 - 100 km	4407	0.1243	0.3050	0	1
100 - 250 km	4407	0.3965	0.4720	0	1
Buffers around cities with populations of 25,000 or more, proportion of sector in					
0 - 50 km	4407	0.3010	0.4312	0	1
50 - 100 km	4407	0.3526	0.4257	0	1
100 - 250 km	4407	0.3010	0.4279	0	1
Vegetation classes, proportion of sector in					
Campinarana	4407	0.0008	0.0164	0	1
Forest	4407	0.6305	0.4506	0	1
Forest-campinarana	4407	0.0053	0.0621	0	1
Pioneer	4407	0.0428	0.1783	0	1
Cerrado	4407	0.2288	0.3901	0	1
Cerrado-forest	4407	0.0912	0.2331	0	1

Map 1. Mean annual rainfall, 1970 to 1996[1]



Map 2. Primary limiting factors of soils



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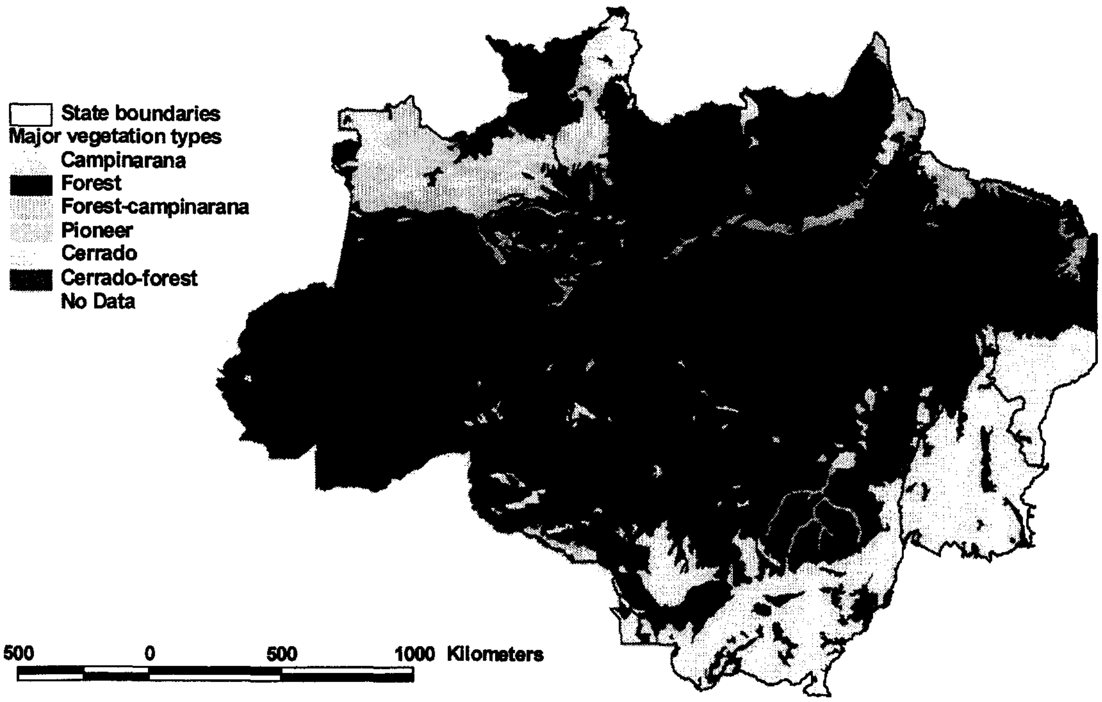
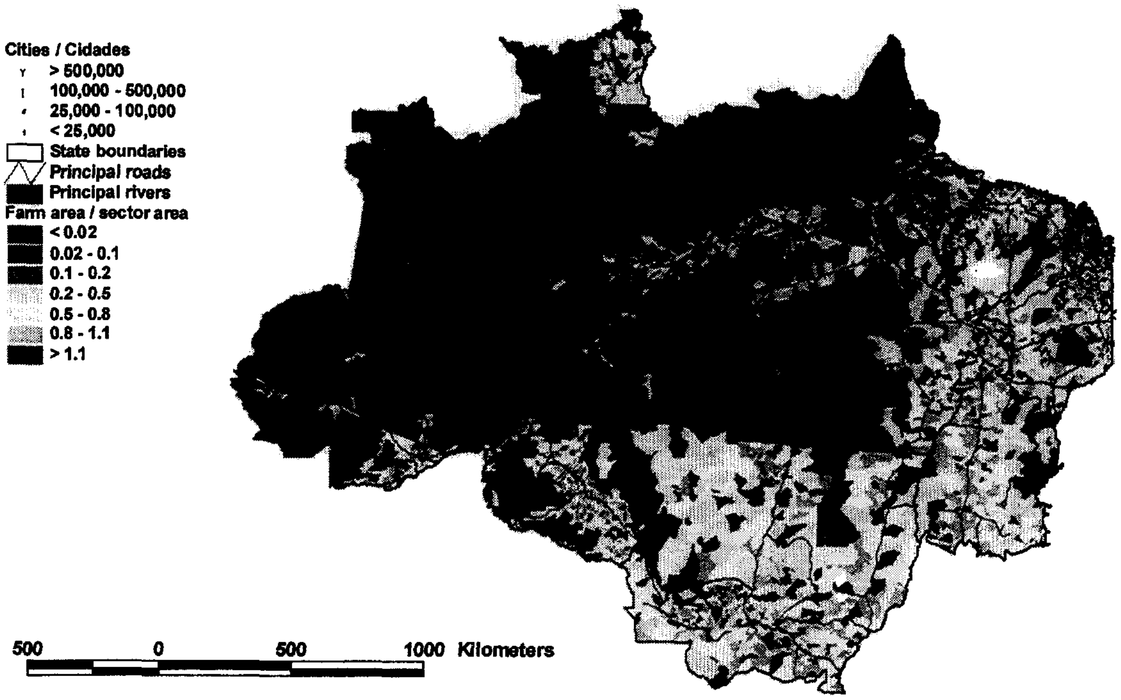
[1] Maps in color are available on the Policy Research Working Papers Web site.

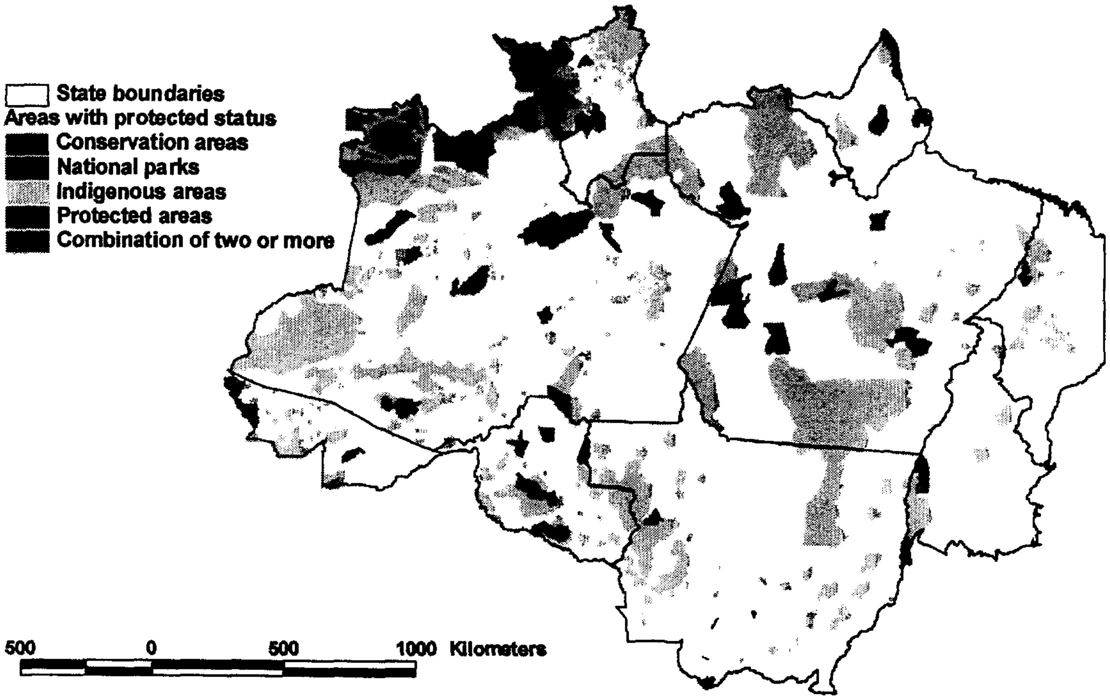
Map 3. Underlying vegetation types



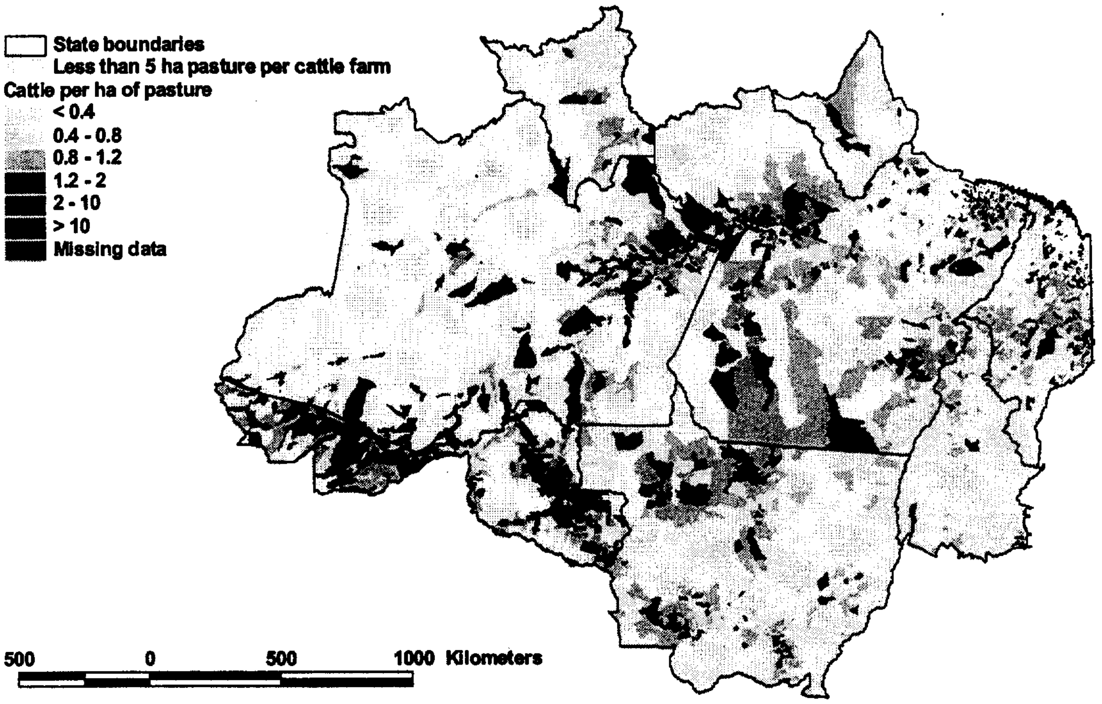
Map 4. Proportion of establishment area in total area of census tract



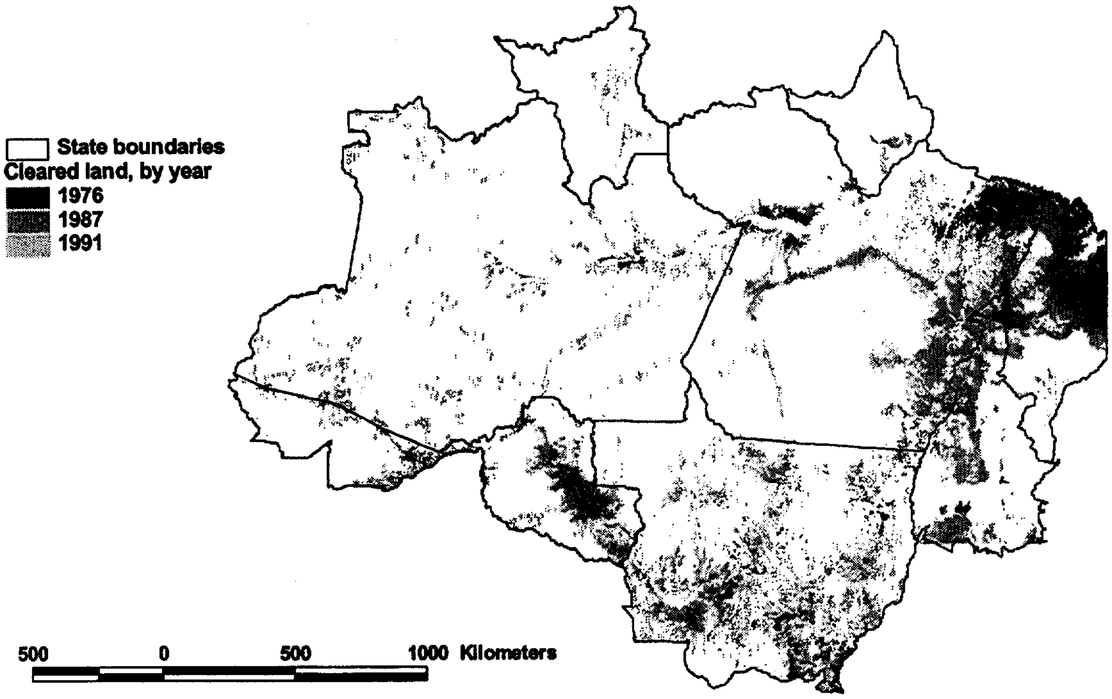
Map 5. Land with some type of protected status



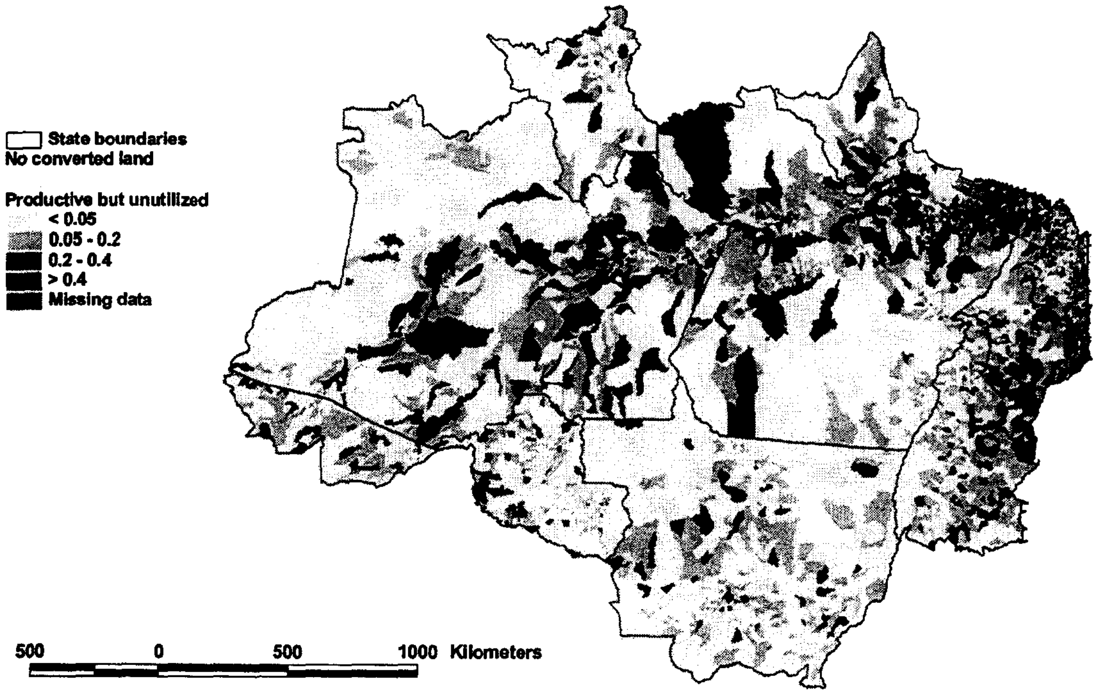
Map 6. Stocking density (cattle per hectare of pasture)



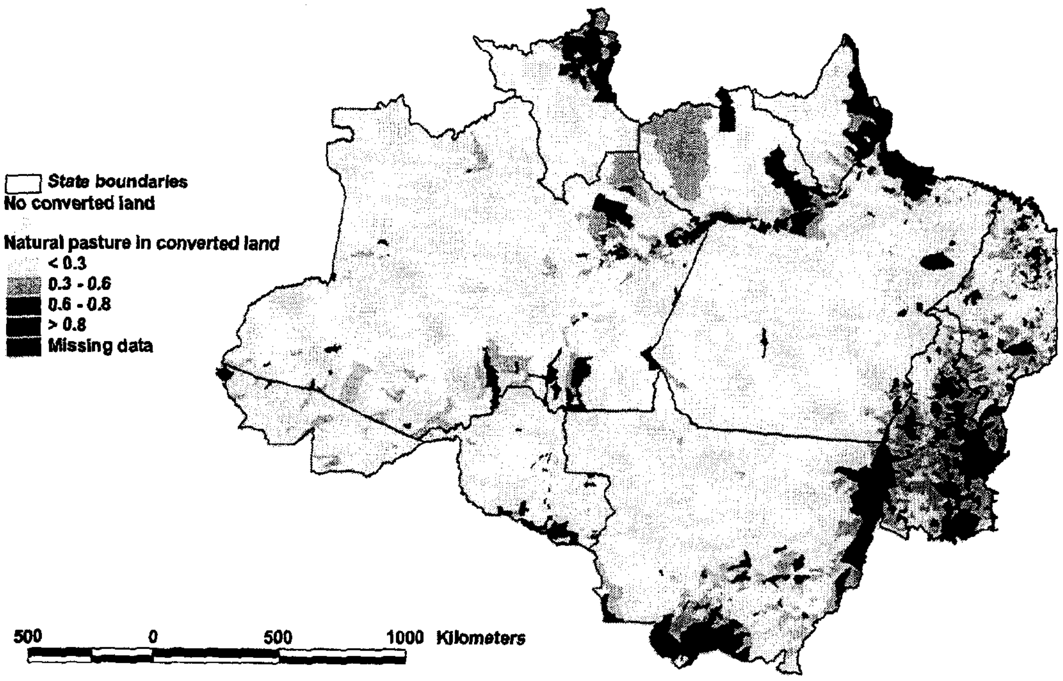
Map 7. Land cleared by 1976, 1987, and 1991



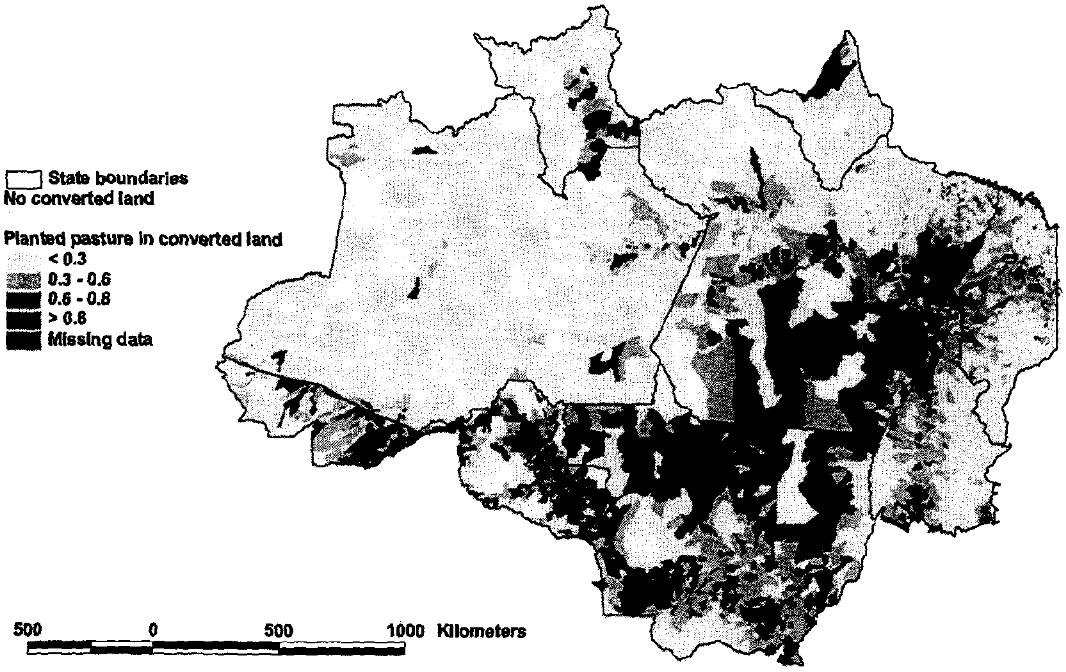
Map 8. Proportion of productive but unutilized land in cleared area



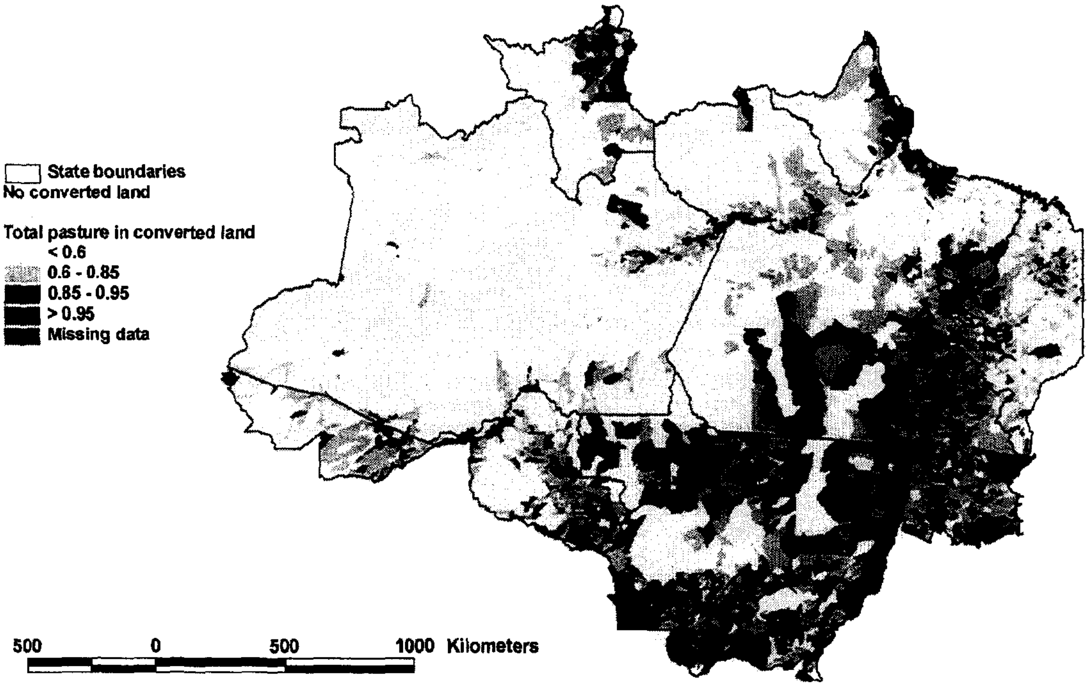
Map 9. Proportion of natural pasture in cleared area



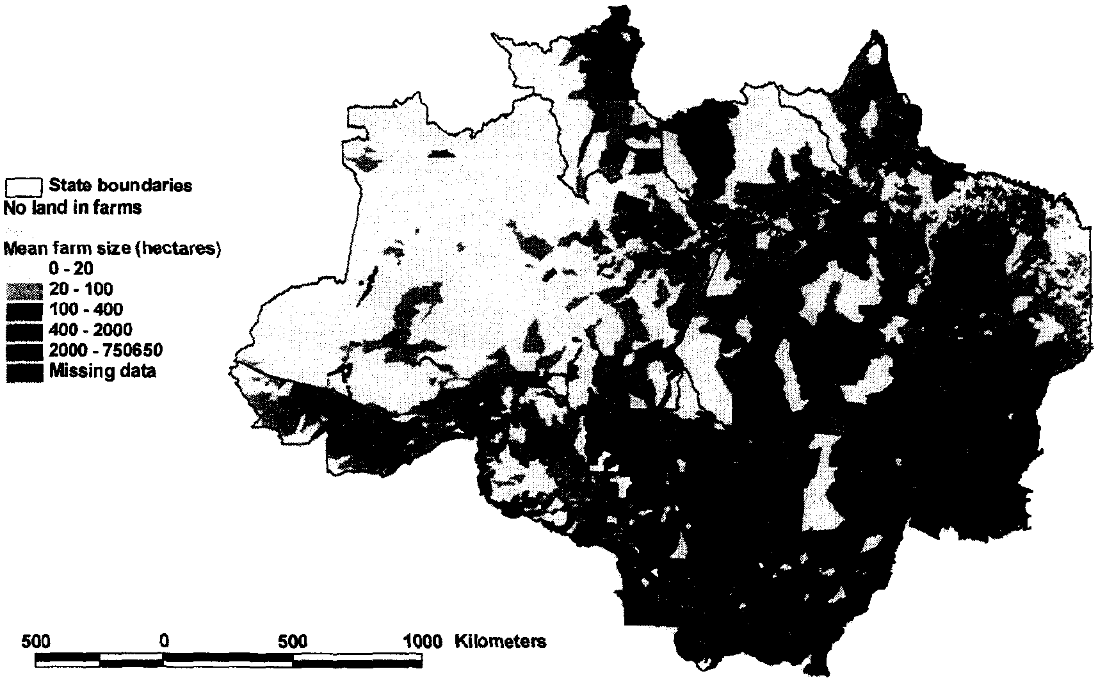
Map 10. Proportion of planted pasture in cleared area



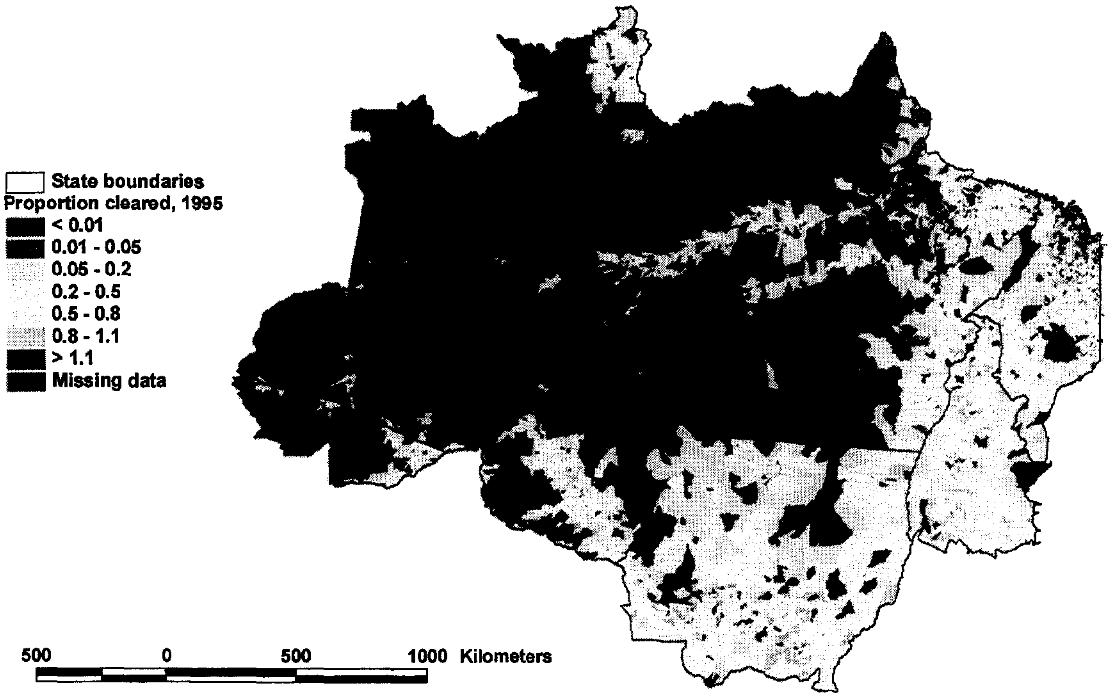
Map 11. Proportion of total pasture in cleared area



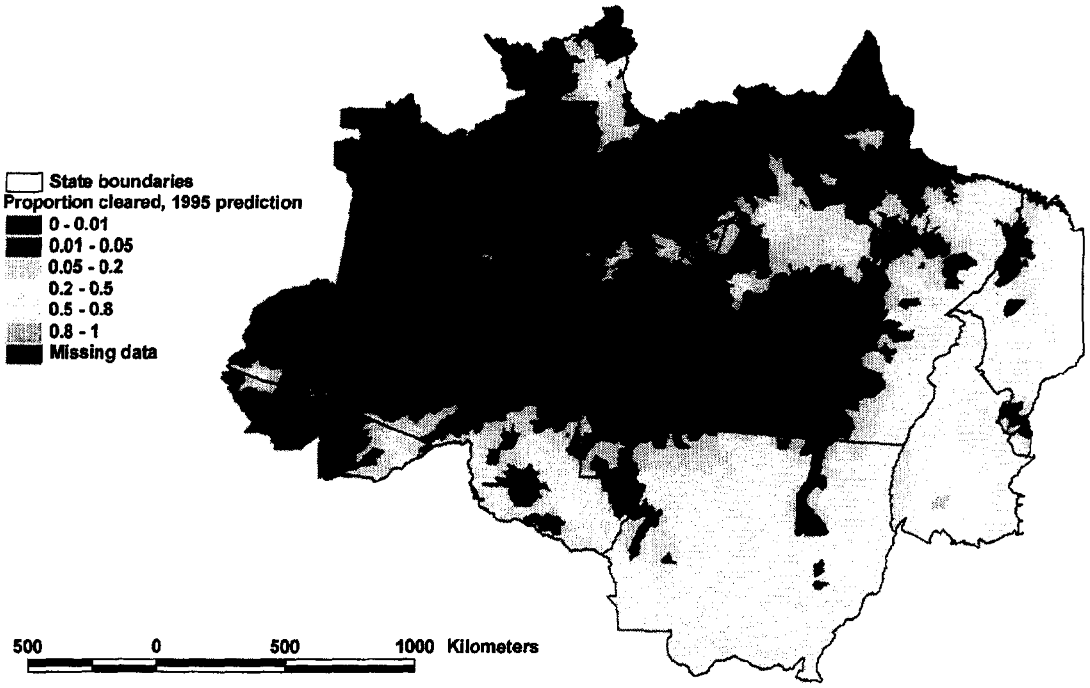
Map 12. Mean farm size



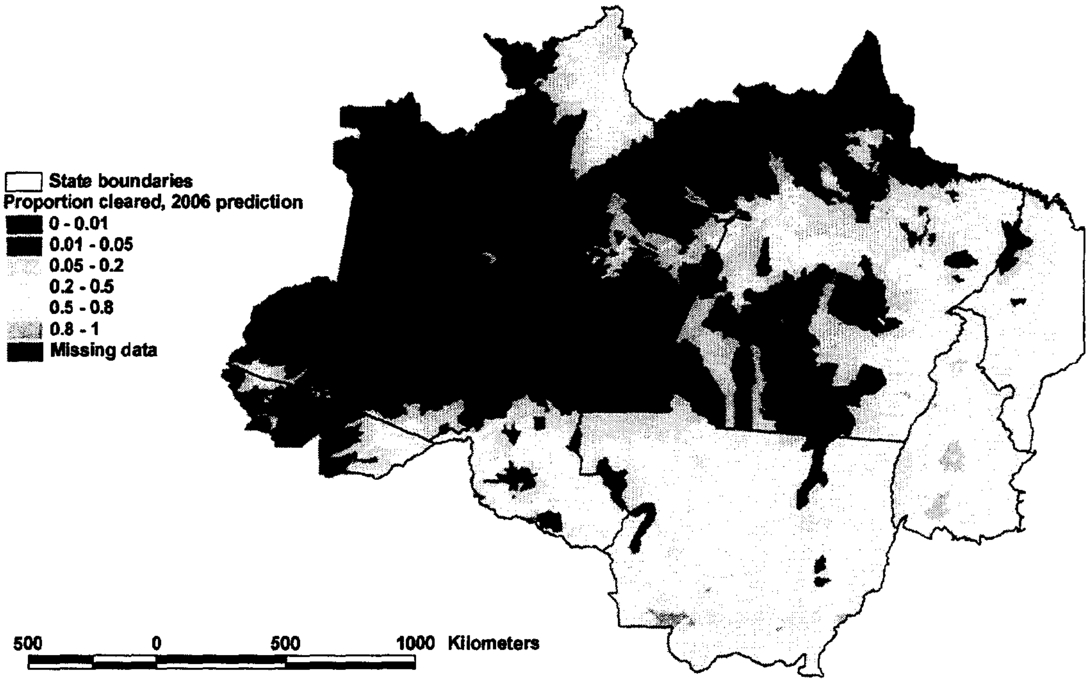
Map 13. Proportion of cleared land in census tract



Map 14. Proportion cleared in 1995 (predicted by model)



Map 15. Proportion cleared in 2006 (predicted by model)



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