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Crossing spatial analyses and livestock economics to understand deforestation processes in the Brazilian Amazon: the case of São Félix do Xingú in South Pará

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Abstract

The Amazon is the largest tropical forest area on Earth, and has been undergoing rapid deforestation for the last four decades. In the Brazilian Amazon, large-scale pasture for cattle ranching and soybean production are the main land uses, leading to a yearly deforestation rate of 0.5%. These conversions are mostly located in frontier areas distributed along the so-called "arc of deforestation". Within this large zone, various land use change processes are interacting through several modes of land valuation and organisation. From several case studies in the State of Pará (Brazil), the current project aims at analysing how landscape dynamics are related to infrastructure development, ecological conditions, zoning policies and to the evolution and the organisation of the production, consumption and marketing chains of livestock products. This paper presents the results for one test site, the region of São Félix do Xingú, South of Pará. This region is the focus of land speculation, cattle expansion, and deforestation. Road construction, investments in electrical energy, financial credit for cattle, and the land reform policies have all fuelled this process. All these factors make this region one of the most dynamic agricultural frontiers in the Brazilian Amazon. The main objective of the paper is to improve our understanding of deforestation processes by crossing spatial analyses and livestock economics studies, and to characterise the role and impact of various natural and anthropic factors in the location and development of the main types of farmers, and their policy implications.

Keywords: Spatial modelling; Livestock commodity chains; Typology of farmers; Deforestation; Brazilian Amazon

1. Introduction

The Amazon is the largest tropical forest area on Earth, and has been undergoing rapid deforestation for the last four decades. For the period 1973–1992, FAO statistics for Brazil report a yearly deforestation rate of 0.48% of the forests in the Brazilian Amazon. The latest estimates for 2000 reveal an increase of the yearly rate of deforestation to 0.58% (INPE, 2001). Alves (1999) shows that deforestation in the 1990s for the entire Legal Amazon tends to be concentrated in limited regions, growing inertially around areas of deforestation and major roads. These conversions are distributed along the so-called "arc of deforestation", from the western State of Acre to the eastern State of Pará, where various land use change processes are interacting between several modes of land valuation and organisation. At least 80% of the deforested areas

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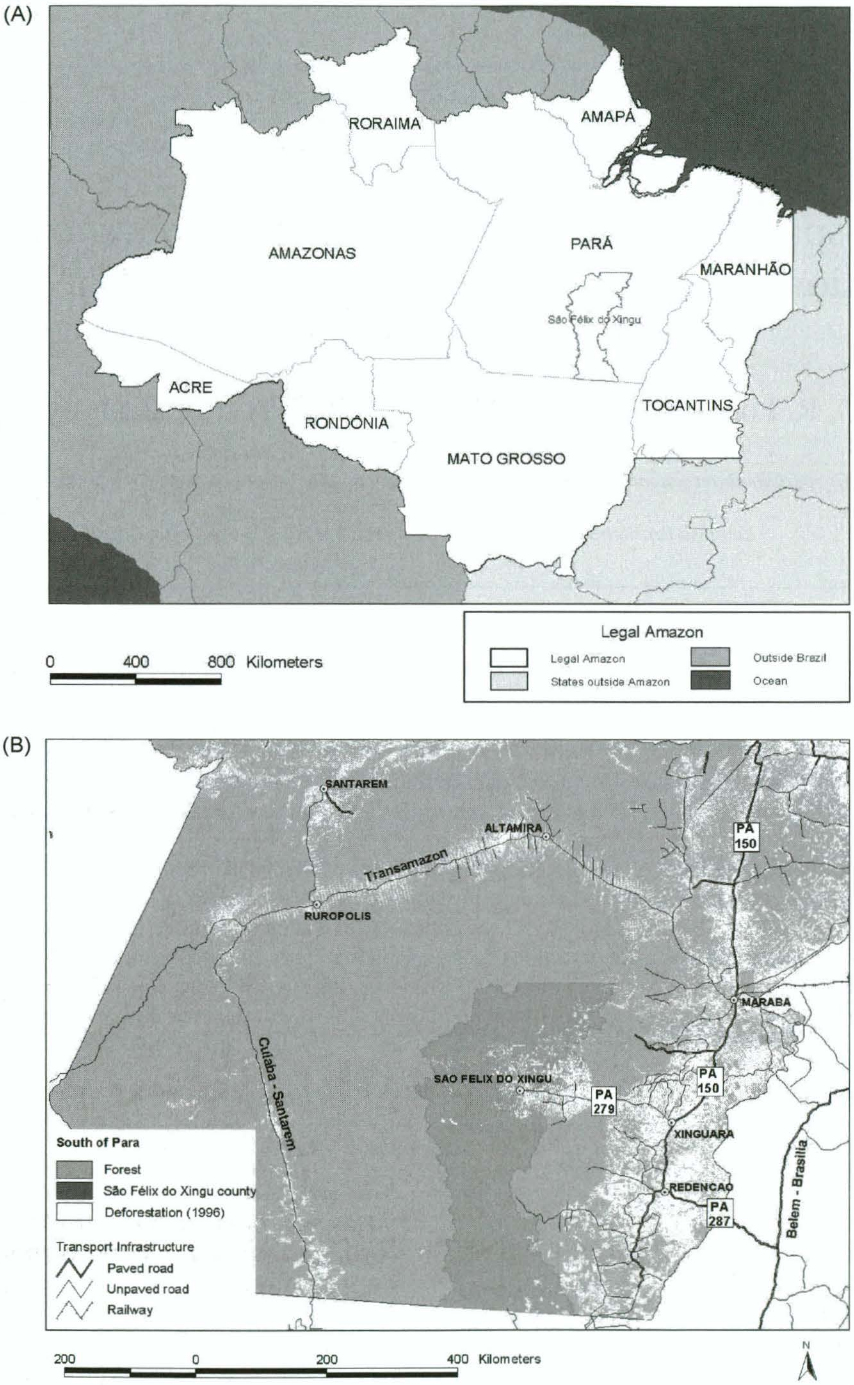

Fig. 1. (A) São Félix do Xingú county in the State of Pará (Legal Amazon); (B) transport infrastructure in southern Pará, around São Félix do Xingú county.

is now under cattle pasture or under secondary forest in pasture that has been degraded or abandoned, and much of the area is in the hands of large landholders (Fearnside, 2001). In the Brazilian Amazon, the expansion of cattle ranching is occurring at such a rapid pace that concerned analysts have adopted the term "pecuarizaçaõ" (*cattelization*) to depict the extraordinary increase in the cattle herd among landholders of all sizes. Indeed, whereas ranching was mainly the domain of large producers during the initial stages of frontier settlement, small farmers are increasingly involved in the production often to the exclusion of other land use options (Veiga et al., 2001).

Early in the 1960s, the Brazilian government decided to initiate a huge development programme to integrate the Amazon region into the national economy. Since then, around 60,000 km of roads were constructed, several hundred thousands people were helped to settle along these roads, billions of dollars of credit were extended at negative real rates of interest and tax breaks and land concessions were offered for agricultural expansion (Andersen and Reis, 1997). Rapid agricultural modernisation in the south of Brazil in the 1970s had left many farm workers and peasants without jobs or land (Barraclough and Ghimire, 2000; Skole et al., 1994). The government's policies were therefore to settle as many as possible of these and other land-seeking people in the "empty" forested areas of the Amazon by providing incentives for large-scale agriculture and cattle ranching (Barraclough and Ghimire, 2000). In response to the national economic crisis during the 1980s, even more people began buying frontier land for the purpose of holding it as a store of value: speculative demand for land became one of the important forces impelling growing numbers of farmers to sell their plots and move on to settle and deforest new frontiers (Almeida and Campari, 1995; Andersen and Reis, 1997). But new patterns have emerged in the late 1980s as small farmers increasingly invested in cattle. Large ranchers and small producers have often been held out in opposition, as two sets of fundamentally different actors. But Walker et al. (2000) emphasised the primacy of the cattle economy across all sectors: large producers are specialised in cattle production, but small producers show an evolution in this direction. One of the main reasons is the multifunctional role of cattle in the farming system: cattle supply the family milk demand, it is a relatively safe form of saving and it contributes significantly to farm income through the commercialisation of milk and calves (Tourrand et al., 1999).

This paper focuses on the region of São Félix do Xingú in southern Pará (Fig. 1). This region is the focus of land speculation, cattle expansion, and deforestation. Road construction, investments in electrical energy, financial credit for cattle, and the land reform policies have all fuelled this process. All these factors make this region one of the most dynamic agricultural frontiers in the Brazilian Amazon. The main objective of the paper, is to improve our understanding of deforestation processes by combining spatial analyses and livestock economics studies, and to characterise the role and impact of various natural and anthropic factors in the location and development of the main types of producers. Complementary datasets were collected, from socio-economic census, key-informants interviews and satellite remote sensing imagery, linked with various geo-referenced information (GIS) on human and biophysical conditions. These data are integrated in a GIS, and used in spatial econometric modelling approaches.

The first part of this paper gives an overview of the regional context and the methodological background. The second part deals with the identification of land use change patterns, as measured through the use of satellite remote sensing. In the Section 3, we examine the structure and evolution of the livestock sector and try to set up a typology of actors. This typology is used to link deforestation patterns to land use change processes (small versus large-scale farmers, directed versus spontaneous colonisation). In the Section 4, all these information are combined with relevant spatial determinants in a geo-referenced database. The spatial statistical models allow us to identify how the relationships between deforestation and a set of explanatory variables vary depending on period analysed and type of farmer. Factors of change and policy implications are presented in the last section.

2. Background

2.1. Spatial statistical models of deforestation

Recent literature reviews of tropical deforestation models have emphasised the great opportunity presented by the rapidly growing availability of spatially referenced data (Lambin, 1994; Kaimowitz and Angelsen, 1998). Spatial statistical models can be especially appropriate to identify and evaluate the relationship between deforestation and spatially-explicit explanatory variables such as accessibility (e.g. Chomitz and Gray, 1995; Cropper et al., 2001; Deininger and Minten, 1996; Mamingi et al., 1996; Mertens and Lambin, 2000; Nelson and Hellerstein, 1997), environmental conditions (e.g. Chomitz and Gray, 1995; Cropper et al., 2001) and land tenure and zoning restrictions (e.g. Chomitz and Gray, 1995; Deininger and Minten, 1996; Nelson et al., 2001; Mertens et al., 2003). These models are well suited for predicting where deforestation will occur and generally involve large samples and reasonably reliable data. While such models say little about what tools are likely to be effective in preventing deforestation, they suggest where these tools or measures should be applied (Cropper et al., 2001).

The basic economic theory underlying practically all these models is that a farmer will deforest an area whenever the gross benefits outweigh the costs. One would expect that deforesting a location with soils, climates, and topography more suitable for agriculture would provide higher farmers incomes than deforesting less favourable areas. When government zoning variables such as protected areas, forest concessions, and colonisation areas are included in the analysis, this implies that farmers may either get additional benefits from deforesting in specific areas or have to pay additional costs for doing so. However, most spatially-explicit studies of deforestation processes have failed to acknowledge that the same geo-referenced explanatory variables can influence deforestation in different ways, depending on the study area sub-regions and the specific time period considered. One of the main weaknesses of such regression analyses is the difficulty to separate correlation from causality, or determine the direction of causality (Lambin et al., 2000). Researchers have attempted to address this issue by incorporating more independent variables and using more data for the independent variables from before the land use changes analysed, but have been only partially successful (Kaimowitz and Angelsen, 1998).

2.2. Previous land use change modelling studies in Brazilian Amazon

Few spatial statistical models have been used in the Brazilian Amazon context. Most deforestation models applied in this region are based on regional regression analyses, and focused on county, state or regional levels (e.g. Andersen, 1996; Andersen and Reis, 1997; Pfaff, 1997). They are categorised as non-spatial regression models since they do not provide any information about the specific location of forest clearing (Kaimowitz and Angelsen, 1998), and they do not take into account the spatial distribution of landscape elements and adjacency effects (Lambin, 1994).

Land use in the Amazon is strongly shaped by past settlement patterns and by roads (e.g. Alves, 1999). More than two-thirds of Amazon deforestation has taken place within 50 km of major paved highways (Alves, 1999; Nepstad et al., 2001) and the Brazilian government's national economic development plan "*Avança Brasil*" would rapidly increase the supply of forest land through the paving of more than 6000 km of roads in the Amazon (Laurance et al., 2001; Nepstad et al., 2001).

Credit and fiscal policies for livestock and crops seems to have stimulated deforestation (Andersen and Reis, 1997). The same authors have looked at the relationships between deforestation and development policies for the period 1970–1985, and concluded that subsidised credit implied a relatively good trade-off between economic growth and deforestation, while large road building projects had a much less favourable trade-off. Intensive transport infrastructures development inside the agricultural frontier seems to have less harmful impact on deforestation than extensive one (i.e. with other region), because it may favour land use intensification (Pfaff, 1997). Moreover, if paving projects within existing frontiers were accompanied by investments in education and health services, as well as marketing facilities, they might foster socially equitable rural development and long-term prosperity (Nepstad et al., 2001).

Pfaff (1997) derived a deforestation equation from an economic model of land use at the county level. His findings show the significance of land characteristics (soil quality and vegetation type) as well as factors which affect transportation costs (density roads and distance to major markets). Chomitz and Thomas

(2000), using multivariate regression analyses, relate forest conversion to biophysical and socio-economic variables at the district-level. The dependent variable was the ratio of agricultural land to area of the census tract. According to their results, most agricultural land is concentrated in large properties in the eastern Amazon and deforestation has led to the creation of low-productivity extensive pasture. Moreover, the probability for land being used for agriculture seems to decline substantially with increasing precipitation levels. Provision of new roads in very moist areas might have limited initial impact on clearing, while road building in drier regions will have a larger immediate effect on forest conversion, and are more likely to result in runaway fires (as shown by Nepstad et al., 1999).

3. The model

3.1. Statistical method

The models constructed are Logistic Regression models whose dependent variable is the presence or absence of deforestation in a particular location during the time period considered. The independent variables tend to capture the accessibility, the land tenure and zoning policies, and the ecological conditions. Logistic Regression is designed to estimate the parameters of a multivariate explanatory model in which the dependent variable Y is categorical (dichotomous or categorical), and the c independent variables X_j are either continuous or categorical. The general equation is (Jobson, 1992)

$$\mathrm{logit}(p) = \ln\left[\frac{p}{1-p}\right] = \beta_0 + \sum_{j=1}^{c}\beta_j x_j \qquad (1)$$

where p is the probability of having deforestation (Pr $Y = 1$); β_n the estimated coefficients.

The computed logistic equations and associated statistics allow us to characterise the role and relative importance of the explanatory variables in determining whether a particular state of the dependent variable occurs, in this case whether a specific location was or was not deforested during the considered period. A set of explanatory variables X_n characterises each location, or *observation*, for the specific period. Each observation corresponds to a $30\,\mathrm{m} \times 30\,\mathrm{m}$ pixel. Eq. (1) gives the probability of each location being deforested as a function of its attributes. Logistic Regressions were performed using the CATMOD function in (SAS/STAT software).

First, separate binary logit models (presence/absence of deforestation) were computed for the two periods, i.e. from 1986 to 1992 and 1992 to 1999. One can interpret the results of the Logistic Regression in terms of logit (Hosmer and Lemeshow, 1989), i.e. the logarithm of the probability of having $Y = 1$, meaning presence of deforestation, rather than $Y = 0$ meaning in this case stable forest. The set of spatially-explicit data used to calibrate the models for each period must characterise the state of each independent variable *at the initial date*, i.e. the state of the variables in 1986 (for the 1986–1992 period) and in 1992 (for the last period). The data used to estimate the models comes from a sample of pixels (or observation) in the GIS data set. That made it possible to work with a large and representative regular sample of >150,000 observations for the entire study area for each period. Second, multinomial logit models were run in order to characterise the role and importance of the independent variables in explaining the forest conversion for specific types of activities or processes of colonisation (cf. typology in Section 3.2). Multinomial logit models are used for the case of dependent variable with more than two categories (Jobson, 1992). Each category is compared to a reference category: in this study, all types of forest conversion are compared to the stable forest category.

Three common statistical problems in models such as these are spatial autocorrelation, multicollinearity and endogeneity (see Anselin overview paper from this special issue). *Spatial autocorrelation* can obscure the results of a regression analysis. Deforestation as a phenomenon is likely to be characterised by spatial autocorrelation, which in general results in inefficient parameter estimates and inaccurate measure of statistical significance. The sampling procedure allows to increase the distance between observations, and thereby to decrease the potential undesirable effects of spatial autocorrelation (Mertens et al., 2003; see Nelson and Geogeghan overview paper from this special issue). *Multicollinearity*: independence of the explanatory variables is a prerequisite of the statistical method used. Variables such as distance to roads and markets tend to be highly correlated, making it difficult to distinguish their separate effects. We tested for collinearity in our independent variables by looking at the coefficient of determination (R^2) between all pairs of variables, and found a weak association between explanatory variables. That implies a relatively low degree of collinearity. The *endogeneity* problem arises because it is hard to distinguish situations where human settlements, productive activities, and infrastructure are located in certain places because those places have environmental conditions that make them good to deforest from those where deforestation occurs because people settle, build roads, or make specific zoning decisions. We have attempted to reduce this problem by controlling for agricultural suitability and using independent variables from a time period prior to the dependent variables.

3.2. Spatial patterns and dominant type of producers

As mentioned earlier, several types of actors are involved in the frontier expansion. The land cover change maps were used to stratify the study area in terms of dominant landscape patterns. Examining these spatial patterns, and combining them with field and socio-economic and livestock commodity chains data, can be a powerful means for linking patterns to processes. The objective of this zoning was to define areas that tended to be affected by a dominant type of land use. The hypothesis is that specific activities (or land use), carried out by specific types of producers, will result in a specific footprint in the landscape, which is detectable on classified satellite images. The four main categories observed in the study area, and further considered in the models, are: small-scale directed colonisation, small-scale spontaneous colonisation, medium-scale spontaneous colonisation and large-scale *fazenda* (Fig. 2). Field interviews show that these categories also reflect contrasting conditions in terms of access to credit, labour and capital availability, level of technology and land tenure regime. The benefit from this methodology should be the ability to locate and quantify the impact of each type of producer: the landscape patterns can therefore be considered as indicators of the social, economic and ecological evolution processes in the region.

For this paper, the zoning of the study area in terms of patterns/processes was carried out by visual interpretation of the land cover change maps. Quantitative spatial indicators of deforested areas, issued from the landscape ecology field (e.g. Turner and Garner, 1990), were then computed using the *Patch Analysis* extension of *ArcView* software to characterise these zones, such as the size, density, shape, and proximity analyses (see, e.g. Baskent and Jordan, 1995; Imbernon and Branthomme, 2001). These considered zones include more than 90% of total pasture/agriculture areas. The use of this stratification allows us first to estimate the relative importance of a land use, and its evolution over time. Then, as input in the spatial modelling analyses, it aims to identify the specific role and relative importance of the potential determinants for a particular land use and the resulting deforestation patterns.

3.3. Data used in the model

Landsat satellite images TM and ETM+ for 1986, 1992 and 1999 were used for this study. In order to cover the entire study area, four images were selected for each date. The selected dates of observation ensure a sufficient interval of time to characterise the landscape dynamics, and to consider particular events related to the macroeconomic and national policies context. The raw images[1] were geo-referenced and classified using unsupervised classification to produce categorical land cover maps for change detection (see Nelson and Geogehan, this issue for more details on classification procedures). Ground truth data were derived from multiple sources. The final classification scheme has seven classes, regrouped into forest/non-forest maps for each date of observation.

The selection of the independent variables to be integrated in the models is based on hypotheses/theories on land use change for this region and on the data availability. These variables were measured for each pixel to capture the potential rent for agricultural land use in

[1] The Tropical Rain Forest Information Center (TRFIC), Basic Science and Remote Sensing Initiative, Michigan State University (http://www.bsrsi.msu.edu/trfic), provided us with several Landsat satellite raw images.

each location as defined by determinants such as accessibility, ecological conditions, land tenure/regime, marketing opportunities, production constraints and access to services. Particular attention was given to collect enough data to describe and map as realistically as possible the state of the considered variables for each time period. For each model, the independent variables depict the situation for the period prior to the dependent variable.

3.3.1. Soil aptitude for agriculture

The only available source of information concerning the soils is the soil map of Brazil (Camargo, 1981), based on soil types and topography. Unfortunately, the 1:5,000,000 scale of the map is not consistent with the scale of analysis for this study. We therefore used in the model a binary variable for presence/absence of relief based on the visual interpretation of the satellite images and field observations. These areas cover

(A)

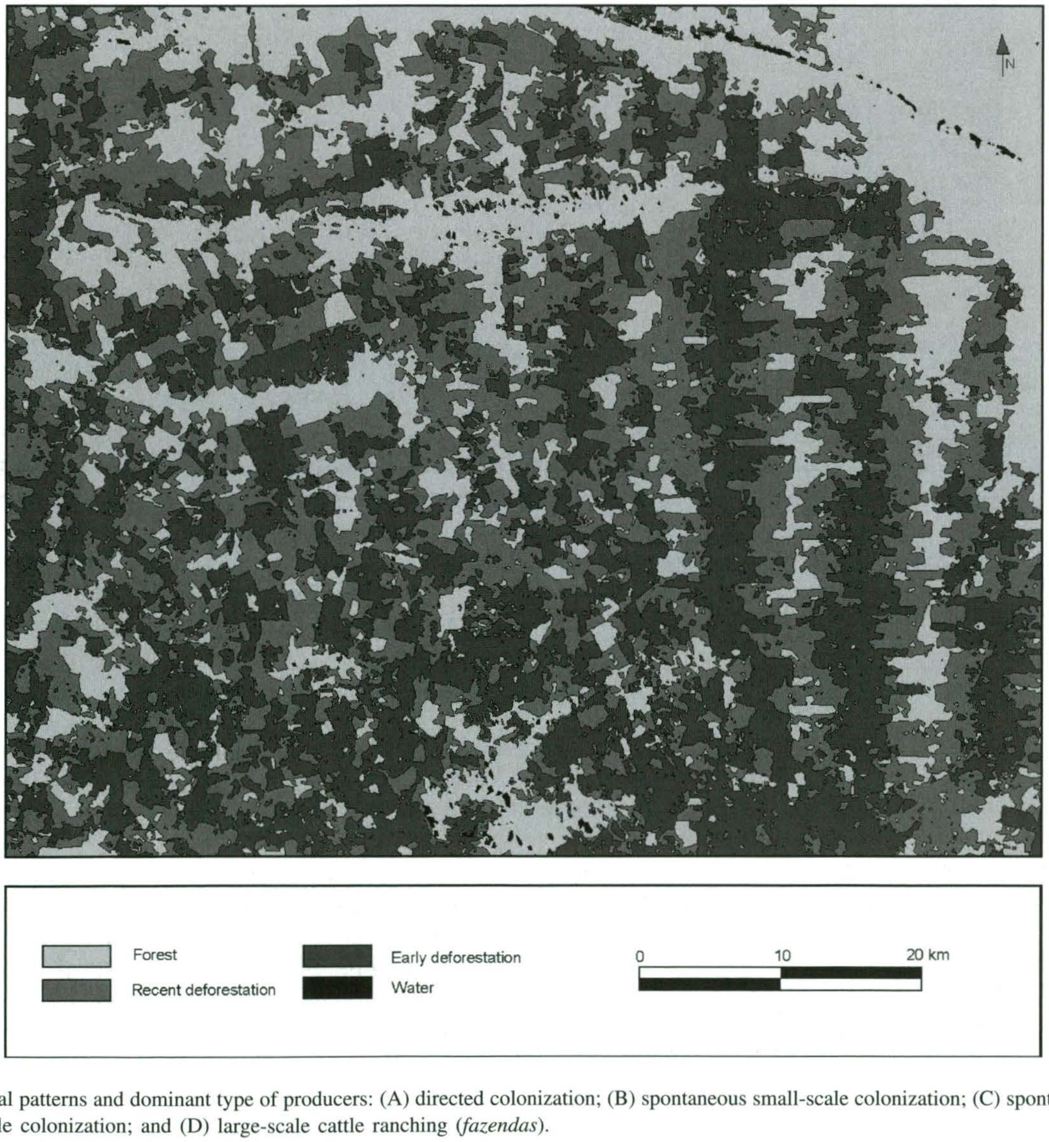

Fig. 2. Spatial patterns and dominant type of producers: (A) directed colonization; (B) spontaneous small-scale colonization; (C) spontaneous medium-scale colonization; and (D) large-scale cattle ranching (*fazendas*).

(B)

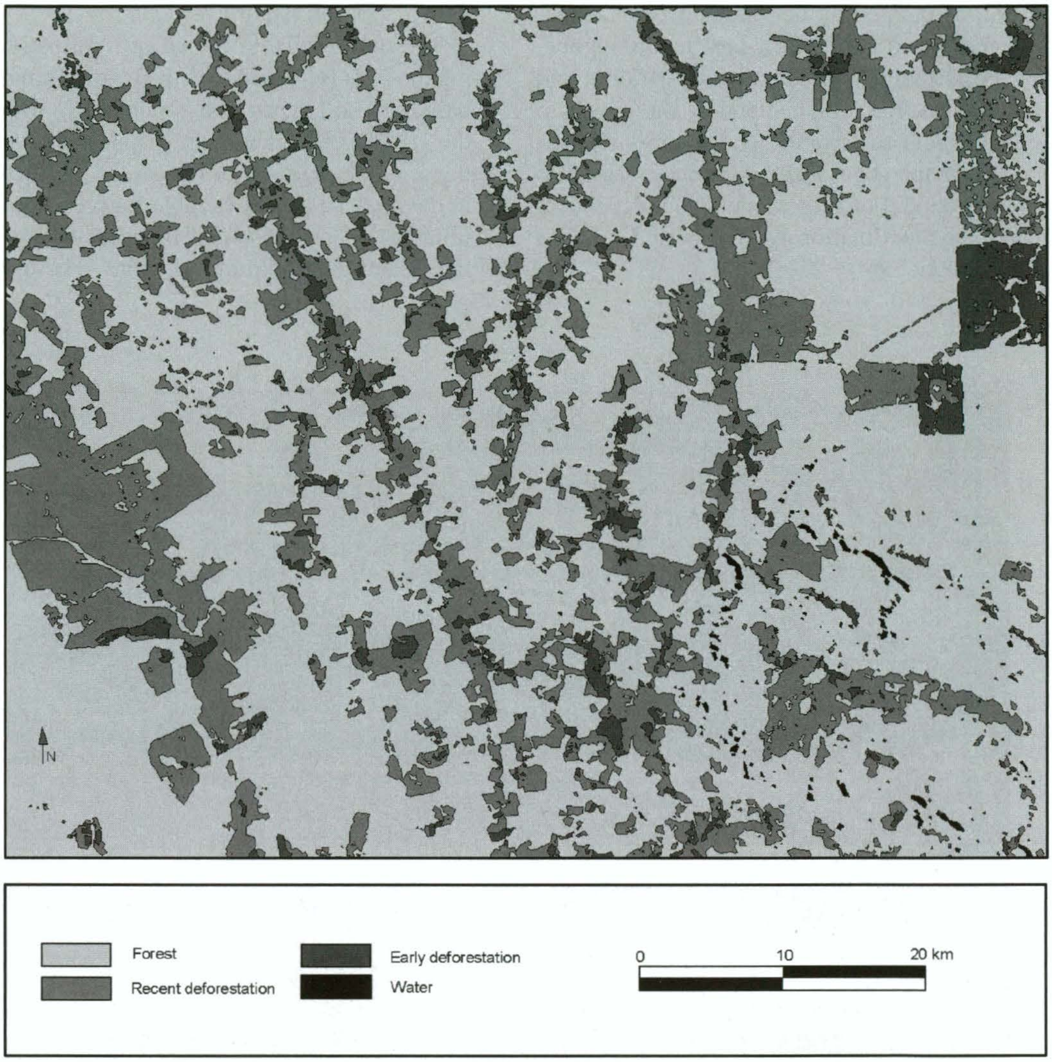

Fig. 2. (B) (*Continued*).

39% of the study area.[2] The presence of relief tends to be a production constraint as it results in higher forest clearing costs, lower yield and higher potential degradation due to soil erosion.

3.3.2. Accessibility

Accessibility was defined as the distance from each location to the nearest river, to the nearest deforested area in the previous period (or forest edge), and to the nearest road. Main and secondary road networks were considered separately. The primary roads, which link São Félix to Xinguára, were built by the State of Pará. The secondary road network, which constitutes the main part of the road network, has been built progressively, and by different types of actors: public or private colonisation organisations (e.g. the Gutierrez project in Tucumã), logging companies (e.g. the northern region, to the *Apyterewa* reserve), and mining companies (e.g. from São Félix to Taboca and Iriri river). These roads were often abandoned

[2] The comparison of this proxy with the soil map revealed a good correspondence between the presence of relief and the occurrence of soil associations types corresponding to low aptitude for agriculture.

(C)

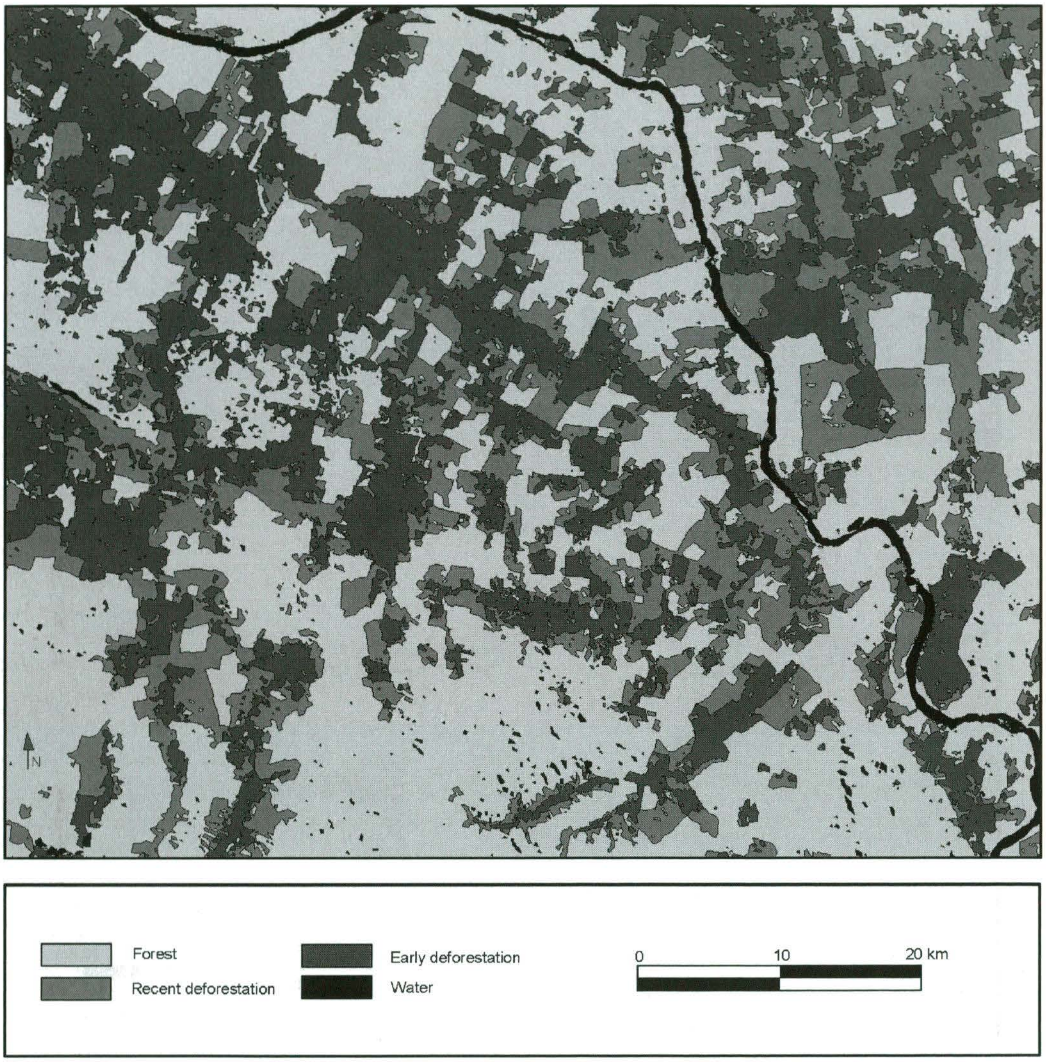

Fig. 2. (C) (*Continued*).

by their initial builders and then further improved by colonists. To a lesser extent, some roads result from spontaneous occupation of large (e.g. *Belauto fazenda*) or small colonists (e.g. Colonia Tancredo Neves). In such cases, the roads are progressively built by colonists, in areas where land is available, and later improved by logging companies, large landholders or public institutions (INCRA). Various sources of information and field observations were used to map the main and secondary road networks, for the time periods considered in the analyses.

3.3.3. Access to services and marketing opportunities

Three variables were measured and included in the GIS database: (1) the distance from each location to the nearest town; (2) the distance from each location to the nearest village; and (3) the distance from each location to the nearest dairy industry. Towns are defined as large population centres, which offer various services such as hospital, schools, bank and administration. Villages are small population centres where one can find schools and small

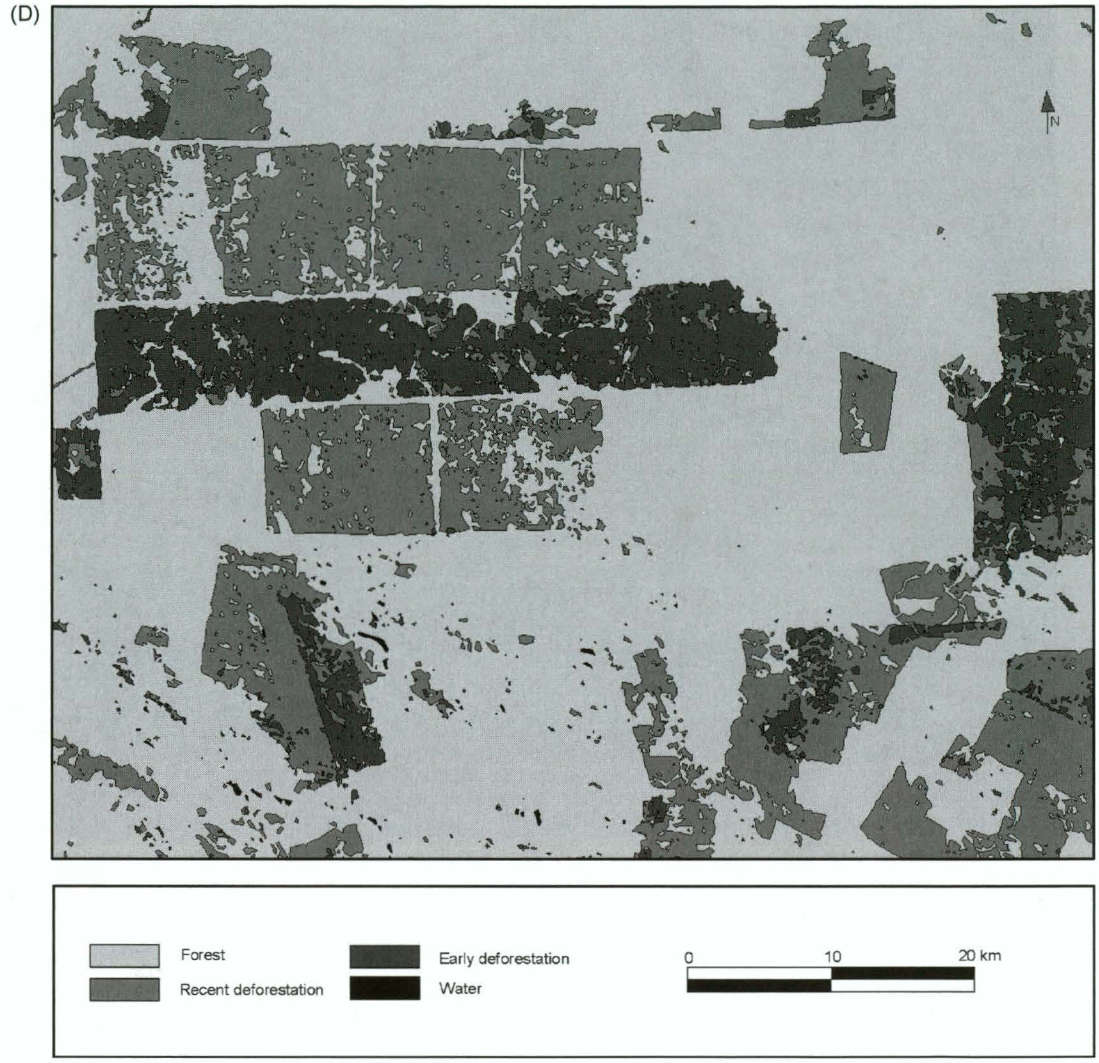

Fig. 2. (D) (*Continued*).

health centres (*posto de saúde*). Dairy industries are the main industrial transformation units in the region (so far, there are no slaughterhouses in the region). These distance values were computed for each time period, considering the installation date of the centres.

3.3.4. Land tenure

The main features to be included in the analyses were the presence/absence of: (1) public- or private-sponsored colonisation zones, and (2) reserve areas (Table 1). Location and related information on the colonisation areas was available at the *Instituto Nacional de Colonização e Reforma Agraria* (INCRA) offices in São Félix do Xingú and Tucumã. These colonisation zones are characterised by specific titling and land regulation. The largest and oldest colonisation zone is located on the main road, around the town of Tucumã (Guitierrez project), while the others are distributed over the study area. Two types of reserves were considered separately: conservation areas and

Table 1
Land area and proportion of the study area by land tenure class

Variables	Area	
	km^2	%
Conservation area	3,557.6	6.3
Indigenous reserve[a]	14,367.4	25.8
Indigenous reserve[b]	9,770.6	17.5
Colonization project (1986)	5,279.3	9.1
Colonization project (1992)	7,208.6	12.4
Colonization project (1999)	7,695.1	13.9

[a] Legal status.
[b] Ongoing regularization.

Table 2
Land cover and land cover change from 1986 to 1999

Land cover (area)	1986	1992	1999
Forest			
km^2	55,156.7	52,207.5	47,809.1
%	98.1	93.7	85.1
Pasture/agriculture			
km^2	491.4	2,940.6	7,839.1
%	0.8	5.2	13.9
Deforestation			
km^2		2,449.1	4,898.4
km^2 per year		408.2	699.7
% per year		0.74	1.33

indigenous territories (a distinction was made between indigenous territories that have a legal status and those that were demarcated but not yet legally recognised).[3]

3.3.5. Administrative boundaries

Finally, a dummy variable was introduced to consider whether a given location is located within the counties of Saõ Félix do Xingú and Tucumã. Those counties contain most of the INCRA colonisation zones and the reserve areas, and correspond to the more remote western frontier area.

4. Land use dynamics from 1986 up to 1999

4.1. The region of São Félix do Xingú

The region of São Félix do Xingú is located in the southern region of Pará, in Eastern Brazilian Amazon (Fig. 1). It is one of the largest counties (84,000 km^2) with a very low-population density (<0.5 inhabitants per square kilometres), 77% of the population living in rural areas. In 1982, after successive cycles of forest resources extraction activities, the road linked São Félix do Xingú to the expanding frontiers areas from Xinguára to Redenção (Schmink and Wood, 1992). From then on, mining activities, wood extraction, small farmer settlement projects and livestock activities stand out as the four successive and complementary drivers of the spatial organisation, confronting indigenous communities which are known for their victorious struggle for their land rights (*Kayapos* Indians). The statistics of the *Instituto Brasileiro de Geografía e Estatisticas* (IBGE) shows a rapid in migration in São Félix do Xingú county; the official population grew from 4954 in 1980, to 24,834 in 1991, and to 40,983 in 1996 (IBGE Census and inter-census data) but these numbers process seems to be underestimated as observed in the field and by Maturana (2001).[4]

São Félix do Xingú is the focus of land speculation, cattle expansion, and deforestation. Road construction, investments in electrical energy, rapid increases in *Banco da Amazônia* (BASA) credit for cattle since 1981, and the land reform policies of the *Instituto Nacional de Colonização e Reforma Agraria* (INCRA) have all fuelled this process (Maturana, 2001). All these factors make this region one of the most dynamic agricultural frontiers in the Brazilian Amazon.

4.2. Land use dynamics in the region of São Félix do Xingú

The interpretation of the time series of satellite remote sensing Landsat images (1986–1992–1999) allows for the characterisation of the land cover change dynamics that affected the region (Fig. 3 and Table 2). In 1986, the muddy water of the *Rio Branco* reveals the intensive nature and location of gold mining

[3] These reserves cover nearly 50% of the study area, and are located at its border. Over the last two decades, access to the area was improved, and the pressure on these reserves has increased consequently.

[4] Indeed, recent field information revealed that the 2000 census population data for the county of São Félix do Xingú was underestimated due to individual political conflicts: the actual population size is estimated to be twice the value of the census.

activities. It is a gold rush period, providing the first colonisation impetus with the arrival of thousands of gold diggers, creating camps that then became towns (e.g. *Ourilândia*). Cleared lands are relatively rare, and mostly located east of *Rio Fresco* (Fig. 3A). One can distinguish small parcels along tracks built in the forest, and well-organised along secondary roads in the Tucumã sector (Fig. 3B). At the opposite, large *fazendas* are already in place, discernable by their size (often more than a thousand hectares), their geometric form and the pasture monoculture. Contrary to small-scale farming systems, these *fazendas* are isolated from the transport infrastructure. The dense network of logging tracks also reveals the intensive extraction of valuable woods, in particular *Swietenia macrophylla*. Finally, three mining sites are observed where large companies were industrially extracting *cassiterite* (roads, airports and extraction sites).

The image of 1992 reveals drastic changes in the landscape (Fig. 3C). The pollution of the rivers has decreased, a sign of the end of gold mining activities, and the forest tracks are not visible anymore, except

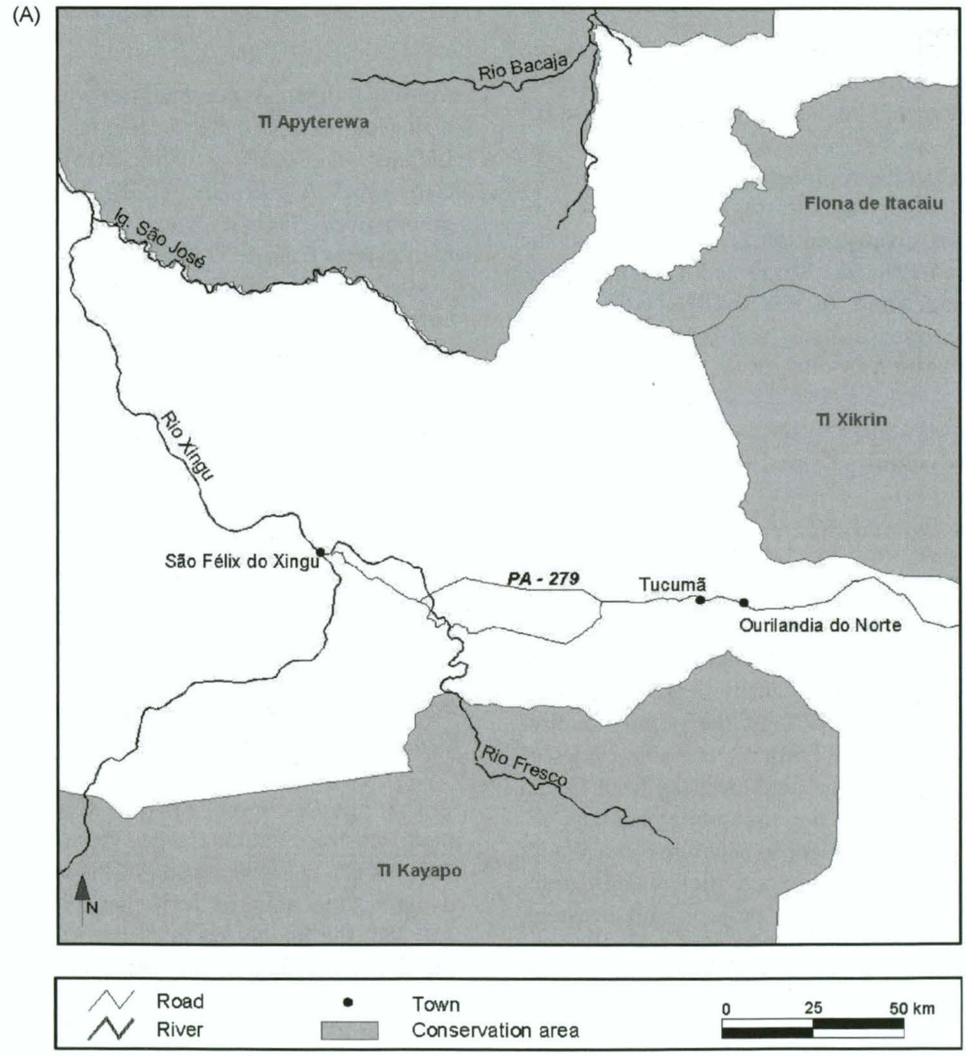

Fig. 3. Land cover changes in São Félix do Xingú and Tucumã for the period 1986–1992–1999: (A) study area; (B) deforestation before 1986; (C) deforestation between 1986 and 1992; and (D) deforestation between 1992 and 1999.

(B)

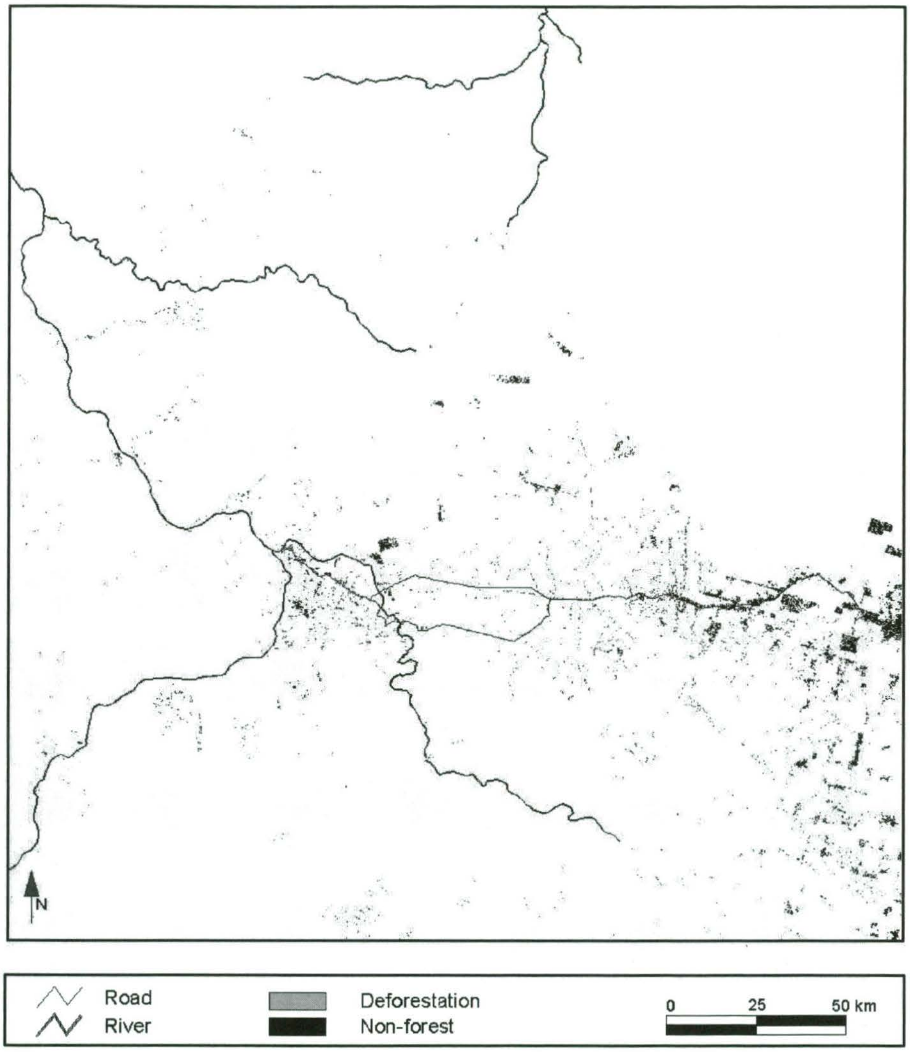

Fig. 3. (B) (*Continued*).

in some areas in indigenous reserves. The small clearing patches observed in 1986 have been replaced by larger pasture areas. They tend to form a thin continuum along the roads, which have been extended. A larger still unpaved road (PA 279) now serves São Félix do Xingú. The number and size of the fazendas has increased. They are now located along the secondary roads as well as in less accessible areas. Similar patterns to those observed in 1986 (small cleared parcels) are now located in the periphery of a core area, where the clearings started before 1986 are now more intensive. This area crossed by the PA 279 is the main axis of the emerging spatial organisation in this period (Schmink and Wood, 1992). Thanks to the spatial and spectral information of Landsat TM, it is possible to distinguish between annual crops, burned areas and different pasture quality. The analysis confirms the predominance of pasture and the presence of annual crops in small-scale farms, which were recently cleared, and in the periphery of the older exploitations (pasture being planted the following year). The juxtaposition of different quality levels

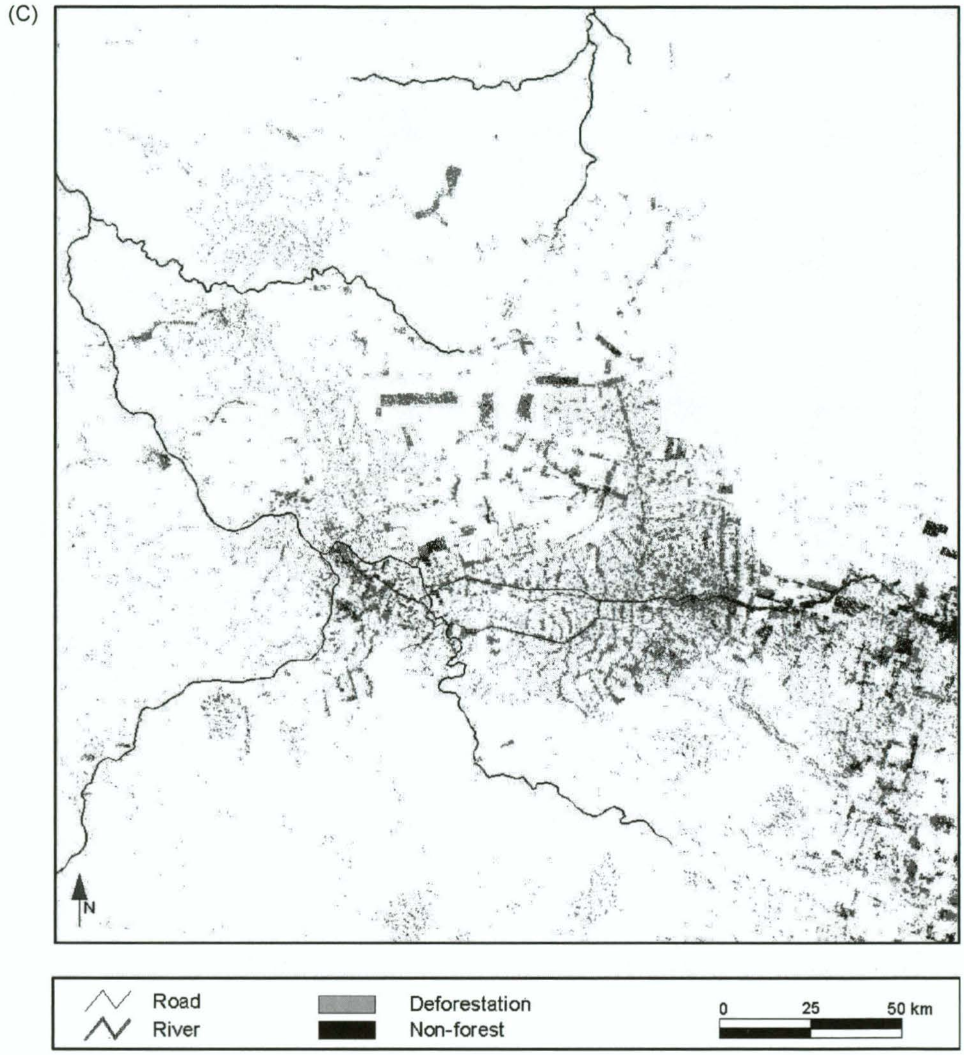

Fig. 3. (C) (*Continued*).

in the pasture reveals the difficulties faced by the producers to control pasture degradation. This is true for small and large exploitations. In some *fazendas*, one can already notice mechanised practices related to pasture management.

The 1999 image reveals a still higher deforestation rate. In the core area, a continuum of pasture monoculture is observed, with some remaining forest galleries along the rivers and small forest blocks as land or fertility reserves for producers (Fig. 3D). Producers have now little room to increase their property size. The number and size of the *fazendas* have increased further, and the 1992 isolated exploitations are now forming larger groups. Some land use patterns reveal the emerging conflicts for the land, such as forest reserves surrounded by pasture in large exploitations (to protect them from invasion), and forest clearings in very isolated areas (>250 km from the PA 279) or in valleys in mountainous areas. In response to the decreasing land availability in the core area, old logging and mining tracks have been rehabilitated, giving access to new forest land which can be acquired by colonists

(D)

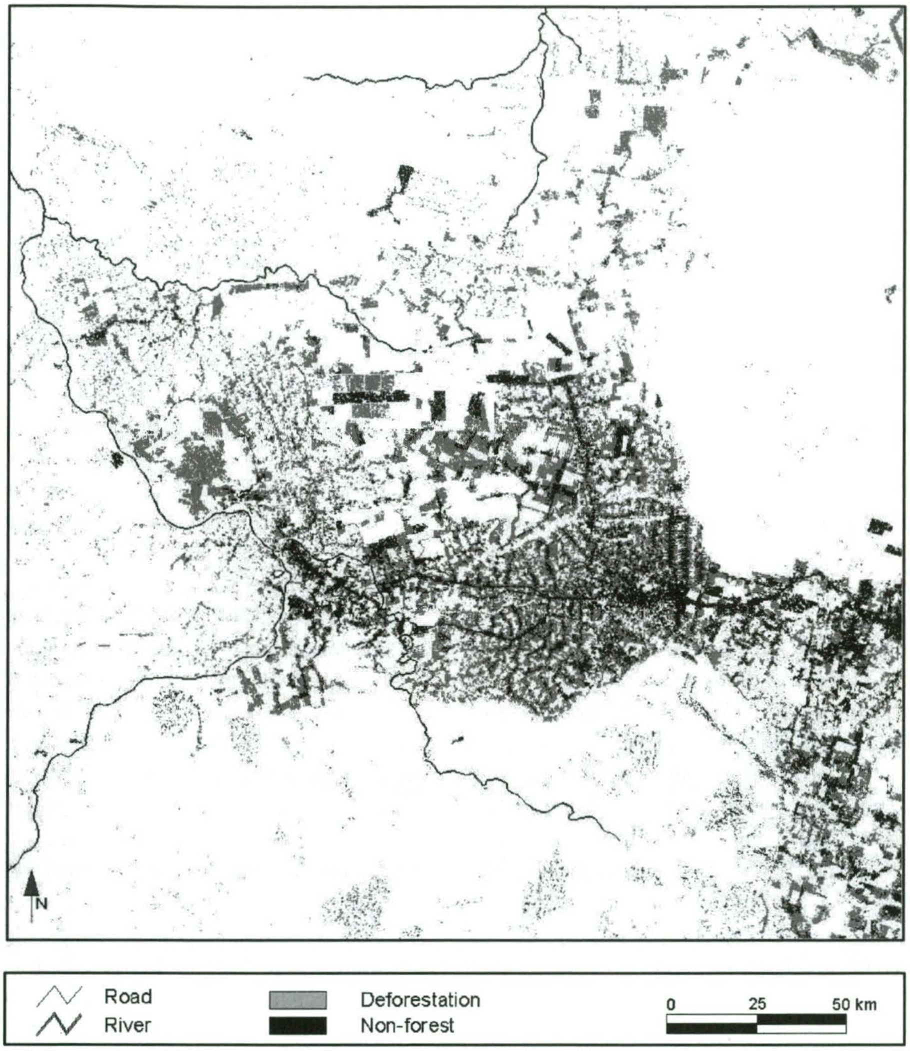

Fig. 3. (D) (*Continued*).

and *fazendeiros* through *grileiros* (falsified land title). An extensive hierarchic secondary road network is developing. The main obstacles for clearing expansion are large rivers (an obstacle to road construction and people mobility) and conservation and indigenous reserves, which are more and more surrounded by pasture, but still crossed by tracks for wood extraction.

For this first period, between 1986 and 1992, the area of deforestation was 2449 km^2 (Table 2). This means 408 km^2 per year, or a yearly rate of deforestation of 0.74%. For the second period, the yearly rate of deforestation reaches 1.33% or nearly 700 km^2 per year. Deforested area between 1992 and 1999 grows to 4899 km^2. Globally, from 1986 to 1999, the forested area converted to agriculture, mainly for pasture, equals 7348 km^2.

4.3. Logging in the State of Pará

Exhaustion of Brazil's southern forests, the opening of roads, plus lax environmental oversight all have contributed to rapid growth of the timber industry in the Amazon. The states of Rondonia, Mato Grosso and Pará provide 93% of the production, from which

86% goes to the domestic market (Lele et al., 2000). In 1993, there were some 2000 sawmills in Pará, producing about 65% of Brazil's roundwood, and generating 13% of Pará's gross product (Verissimo et al., 1998). The same authors estimated that around 80% of the approximately one million square kilometres of forest in Pará is economically accessible: the most accessible areas being located along the Belem-Brasilia and Pará 150 Highway (Fig. 1), and along the Amazon River. Predatory extraction is widespread, leaving about 41 species at risk of extinction due to poor management (Verissimo et al., 1998), increasing forest flammability (Nepstad et al., 1999), and increasing the pressure on high value timber, such as mahogany. Selective logging is spreading across this state in an unplanned and unregulated fashion (Verissimo et al., 1998). The first modern mahogany loggers arrived in southern Pará in the early 1960s, trees were preferentially cut in proximity to rivers and floated to Belem (Schmink and Wood, 1992). In the early 1970s, taking advantage of the Pará Highway 150 (Fig. 1), sawmills began to be established in the towns of Redenção and Xinguára (Verissimo et al., 1995). In the period from 1970 to the early 1990s, the distance between logging areas and sawmills grew from only a few kilometres to >500 km. The same authors estimated that some 3000 km of roads had been constructed by loggers, and many of these roads radiating out from Tucumã, and they noted that logging activities were increasingly concentrated in the region between the Xingú and the Iriri rivers (Verissimo et al., 1995), west of our study area. In addition to providing loggers with access to wood stocks, these roads offer entry points for settlers seeking land, as discussed earlier.

5. Livestock dynamics and spatial structure of landscapes

5.1. Pasture dynamics

Pasture extension in the Amazon frontiers reflects the livestock development because forage is the only feeding source for cattle. But pasture also corresponds to several functions for actors in agricultural frontiers such as the region of São Félix do Xingú (Table 3 shows the rapid increase of cattle herd size in the study area's counties, particularly in São Félix do Xingú).

Table 3
Evolution of the cattle herd size in the study area

County	1980[a]	1990[b]	1996[a]	2001[c]
Ourilândia do Norte		45,875	147,960	190,733
São Félix do Xingú	22,535	34,637	72,840	939,177
Tucumã		20,835	99,875	350,169

[a] IBGE census data.
[b] IBGE estimation data.
[c] SAGRI cadastration (Secretariat for Agriculture).

Pasture creation serves three purposes. First, it generates animal feed; the agro-ecological conditions in the region promote great forage production thanks to appropriate temperature, humidity and soil fertility compared to other Brazilian ecosystems such as *caatinggas* and *cerrados* (Veiga et al., 2001). Second, it facilitates *land appropriation.* Brazilian legislation recognises the right *de posse*, which is a first step towards ownership, obtained by the land occupation and use. Pasture is the main land use, and is the most widespread strategy among all actors, cattle grazing being the cheapest and most efficient way of getting land control (Veiga et al., 2001). For many years, ranchers have considered themselves to be obliged to clear forest to guarantee their tenure because any landowner who did not clear would lose the land either to expropriation or invasion (Fearnside, 2001). Third, pasture creation *increases the land value* at lowest cost and for a long term: given the large size of the clearings, livestock grazing on pasture is the only land use that can cover such areas, and avoid rapid forest regrowth. The price of a hectare of pasture is 5–10 times higher than a forested area, and the demand is permanent to develop livestock production.

Whether for economic, juridical or agricultural purposes, pasture is seen as the best land use in the context of land speculation, even in the absence of a concrete speculation project. These three functions are present and combined in the strategies of most of the actors, even in urban areas. The struggle for land is a lucrative activity, where almost all actors are involved (retailers, loggers, farmers, ranchers, etc.). Note that the last functions are closely linked with the first one, i.e. there is no land speculation and valuing without a livestock dynamic which makes this land market viable. Livestock activities therefore indirectly determine the land use strategies, for all diverse actors.

5.2. Livestock commodity chains and marketing channels

One can distinguish three types of channels for the livestock products in the region of São Félix do Xingú (Poccard-Chapuis et al., 2002): (1) short channels for local consumption; (2) long channels for distant markets; and (3) channels for calves. There are two main categories of producers, i.e. small-scale family agriculture and large-scale ranchers or *fazendas*.

Small producers were in the first period mostly linked to the short channels, which target local urban markets (within the county), characterised by a constant and relatively high consumption. This high consumption was first stimulated by the influx of mining and logging companies. In the first years, supply of livestock was lower than demand, because of the rapidly developing towns, and a small cleared area for pasture. These markets were also characterised by no quality exigency, allowing for the most extensive production systems. Nowadays, lower prices for cattle production are found in these markets, and local consumption relies essentially on the poorest product quality.

The real impulse for livestock came from the emergence of long channels, i.e. to market beef on national markets in the northeast or southeast Brazilian cities.[5] Thanks to the emerging road network in the late 1970s, the large distant markets became accessible for regions of the Amazon, such as the South of Pará. Those regions took advantage of the land availability, the ecological conditions (favourable temperature and rainfall for pasture compared to the drier *cerrados* regions), and the lower production costs. This has promoted the rapid development of the large *fazendas*, specialised for cattle fattening, a strategy for lower cost and risk minimisation. Since the 1990s, four big refrigeration firms were built in the South of Pará (Tourrand et al., 1999; Poccard-Chapuis et al., 2002).

The high demand from large markets has stimulated the emergence of the last channel: the establishment of channels for calves which results from an increasing local demand from the large *fazendas* of the South of Pará. In 1999, the Secretariat for Agriculture recorded >30,000 calves coming each month from the *Cerrados* regions of Tocantins, Goias, Minas Gerais and Nordeste. The high intensity and distance of these inflows reveal a regional deficit in the calves market, which could be supplied locally to decrease the transaction costs. This is the niche where small-scale farmers integrate the cattle chains by developing calf production within diversified systems (Ferreira, 2001). Since the end of the 1990s, the calf production in small farms is frequently combined with milk production, thanks to the establishment of dairy industries in the region. These industries are integrated in the same long channels for beef.

This regional marketing system is therefore characterised by the secure demand from large consumption centres. This is particularly relevant for farmers' strategies in the context of developing agricultural frontier areas, and explains livestock dynamics and associated landscape patterns observed since the 1980s. Results from extensive field interviews of all type of actors in southern Pará reported by Veiga et al. (2001) show that among the most important factors influencing the decision to invest in cattle are: (i) the access to market for meat and dairy products; and (ii) the secure return from livestock activities. These two factors are viewed positively for >95% of the persons interviewed. For several economic and technical reasons (such as, particularly, price stability and pasture management flexibility), cattle ranching, and especially fattening, appears to be a very low-risk activity, in comparison with others agricultural activities. This is why, despite strong government incentives to promote other farming systems and low mean profitability, cattle ranching remains the preferred alternative (Veiga et al., 2001; Piketty et al., 2002).

5.3. Regional livestock dynamics

During the 1990s, new factors have affected the organisation of livestock commodity chains, the actors' strategies, and thereby the land use. Some factors were related to the macroeconomic conditions, such as the Real Plan. By introducing monetary stability, the Plan reduced the importance of the savings functions of cattle and undermined the extensive production systems. Other factors were related to national and regional public policies, such as the fiscal incentives provided by the State of Pará in order to develop local

[5] Since 2000, the marketing of beef products to the southeast regions is forbidden because of the presence of foot-and-mouth disease in South of Pará.

processing factories. The improvement of the infrastructure has promoted these technological changes.

The improvement of the road network, the transport capacity and the bringing of electricity to rural areas have generated new industrial strategies, along with the installation of large processing units within the area, which have made remote forest areas more likely to be converted to pasture. For the slaughterhouses, the installation close to the production basins not only reduces transportation costs, but it also makes stock management easier. These conditions should attract big national companies that manage their production in the region in line with transformation units located elsewhere in Brazil. Finally, the concentration process in the distribution sector gives to emerging actors a preponderant power for negotiation in the marketing chain. Their dominant position in the distribution sector has increased the quality demands. Sanitary regulations have gradually imposed refrigeration of livestock products from industry to consumer, and have led to a reform of the industrial and transport system which gradually guarantees the national quality standard.

All these elements clearly show the current integration of Amazonian livestock within the national market. This stimulates two types of land use strategy. The first is extensive production, i.e. the farmer takes advantage of the initial high pasture productivity. After 3–4 years, the pasture is abandoned and new forest areas are converted to pasture, leading to increasing deforestation rates. The second involves intensification of production (e.g. pasture management, sanitary conditions, improved pasture varieties). This strategy is identified in the landscape by the mechanised recuperation of degraded pasture (due to extensive management), mostly located near the transport network. However, either for small farmers or large ranchers, Fearnside (2001) notes that the costs associated with maintaining productivity of pasture are much higher than the cost of buying pasture or forest land, and therefore discouraging intensification of pasture as long as land is available.

6. Spatial modelling of deforestation patterns

6.1. Results for the entire study area

First, binary Logistic Regression models were run for each period: before 1986, from 1986 to 1992, and 1992 to 1999.[6] This method is used to model the presence or absence of deforestation with regards to the value of the independent variables. The overall fits of the models are significant for the three periods, with pseudo-R^2 ranging from 0.29 to 0.34. Parameter estimates and associated statistics of the models are shown in Tables 4–6.

Results indicate that the occurrence of deforestation prior to 1986 is located outside the reserve and mountainous areas, close to the main road, and far from the villages. Note that most of the villages existing before 1986 are remote mining centres, located far from the towns and main road, and did not lead to further forest conversions. The 1980s correspond to the beginning of the colonisation of the counties of Saõ Félix do Xingù and Tucumã.[7] Deforestation occurred primarily within the more accessible eastern counties, and along the main road PA-279 (e.g. *Ourilândia do Norte* and *Agua Azul do Norte*).

Over the second period (1986–1992), deforestation still tends to be located outside the reserve areas and the mountainous areas, far from the villages and close to the main road. But, as the agriculture frontier is progressively moving to the western forested areas (Fig. 3C), the relative importance of being located within the eastern counties sharply decreased. Most deforestation tends to be located near deforested areas, illustrating the spread effect of deforestation. Similarly, the occurrence of deforestation is increasingly associated with proximity to the emerging networks of dairy industries and secondary roads. Although some deforestation areas are observed in the colonisation project of Tucumã, as it was the only INCRA settlement initiated in the eighties, this parameter was not significant.

Finally, over the third period (1992–1999), agriculture and pasture areas spread around previously deforested areas, and along the network of the secondary road and dairy industries (related to the improved marketing networks). Locations within colonisation zones and within the eastern counties show a higher relationship with the occurrence of deforestation. The reserve areas have the same impact, while the mountainous

[6] For the period before 1986, agriculture and pasture areas observed on the 1986 image were considered as the presence of deforestation.

[7] The Gutierrez private colonization project was initiated in 1982.

Table 4
Estimates for the binary Logistic Regression model predicting the probability of deforestation for the period before 1986

Variable	β	S.E. (β)	Wald χ^2	Significance[a]
Presence of colonization zone	−0.5449	0.0799	46.491	<0.0001
Presence of reserve	−1.9318	0.1231	246.281	<0.0001
Presence of relief	−1.3579	0.0763	316.864	<0.0001
Distance from town	−0.0055	0.0036	2.2434	0.1342
Distance from village	0.0337	0.0026	162.140	<0.0001
Distance from dairy industry	–	–	–	–
Distance from the main road	−0.0399	0.0029	183.775	<0.0001
Distance from the secondary road	−0.0173	0.0047	13.504	<0.0001
Distance from the main river	−0.0012	0.0017	0.0503	0.4781
Distance from forest edge	–	–	–	–
Within counties	−0.3719	0.1363	77.449	<0.0001

Note: β: maximum likelihood estimate of the parameter, S.E. (β): estimated standard error of the parameter estimate, Wald χ^2: Wald χ^2-statistic.
[a] P-value of the Wald χ^2-statistic.

Table 5
Estimates for the binary Logistic Regression model predicting the probability of deforestation for the first period (1986–1992)

Variable	β	S.E. (β)	Wald χ^2	Significance[a]
Presence of colonization zone	−0.2045	0.0512	15.192	0.0405
Presence of reserve	−1.5521	0.0731	451.022	<0.0001
Presence of relief	−0.5216	0.0398	171.989	<0.0001
Distance from town	−0.0056	0.0018	0.001	0.9747
Distance from village	0.0123	0.0014	81.867	<0.0001
Distance from dairy industry	−0.0132	0.0009	227.237	<0.0001
Distance from the main road	−0.0091	0.0016	10.173	0.5844
Distance from the secondary road	−0.0187	0.0021	80.299	<0.0001
Distance from the main river	−0.0027	0.0010	7.8295	<0.0001
Distance from forest edge	−0.4099	0.0154	709.681	<0.0001
Within counties	0.3511	0.0726	23.405	<0.0001

Note: β: maximum likelihood estimate of the parameter, S.E. (β): estimated standard error of the parameter estimate, Wald χ^2: Wald χ^2-statistic.
[a] P-value of the Wald χ^2-statistic.

Table 6
Estimates for the binary Logistic Regression model predicting the probability of deforestation for the second period (1992–1999)

Variable	β	S.E. (β)	Wald χ^2	Significance[a]
Presence of colonization zone.	0.6101	0.0292	436.605	<0.0001
Presence of reserve	−1.5483	0.0476	558.344	<0.0001
Presence of relief	−0.1697	0.0270	35.786	<0.0001
Distance from town	0.0191	0.0017	32.292	<0.0001
Distance from village	0.0038	0.0008	22.331	<0.0001
Distance from dairy industry	−0.0191	0.0011	285.959	<0.0001
Distance from the main road	−0.0098	0.0014	51.618	<0.0001
Distance from the secondary road	−0.0482	0.0013	140.873	<0.0001
Distance from the main river	0.0049	0.0005	87.119	<0.0001
Distance from forest edge	−0.6727	0.0148	2,078.827	<0.0001
Within counties	0.1919	0.0519	13.656	0.0002

Note: β: maximum likelihood estimate of the parameter, S.E. (β): estimated standard error of the parameter estimate, Wald χ^2: Wald χ^2-statistic.
[a] P-value of the Wald χ^2-statistic.

areas, which are still constrain forest conversion to other land use, are becoming more and more affected by deforestation as the pressure on land increases.

6.2. Results by type of producers

The first type of producers considered is small-scale directed colonisation. This category is characterised by a geometric and well-organised pattern of small non-forest areas (Fig. 2). It includes mostly agriculture and pasture in old colonisation areas. It progressively gives rise to a quasi-continuum of pasture and agriculture areas around the town of Tucumã. It is mostly small-scale farmers, even though some medium-scale properties have emerged through land concentration processes: but these concentrations are not the dominant component of the landscape. Within the study area, approximately 40% of total deforestation is attributed to this type of land use (Table 7). For the two periods of time, this specific land use category is mostly associated with proximity to the previously deforested areas. The importance of proximity to primary and secondary road networks, and to the dairy factories increased in the second period (Tables 8 and 9). This type of agricultural activity is found mostly within colonisation zones. The importance of the proximity to the nearest village increased over time, along with the development of the settlements in the area.

The second largest land use category in terms of contribution to total deforestation is the large-scale ranches (*fazendas*). Forests are converted exclusively into pasture. They contribute to 30% of deforestation in the first time period, and 38% for the second period. The associated landscape pattern, i.e. their geometric form and their huge size, make them easy to identify on the land cover maps. For both time periods, large fazendas tend to be located outside colonisation zones and reserves. At the initial stage of frontier expansion, large fazendas are preferentially located on flat areas, and near the main roads. In the second period, they seem to spread near previously deforested areas, and along the secondary roads.

The medium-scale colonisation category contributed for 20% of deforestation between 1986 and 1992, but only for 10% after 1992. These patterns tend to be located outside the colonisation zones, near deforested zones, and on flat areas (although the relationship with the topography variable is stronger for the first period than for the second, as the pressure on marginal land increases). Accessibility seems to be an important, but changing, locational factor. The occurrence of medium-scale colonisation is associated with the proximity of towns and main roads before 1992, but to the proximity of villages, dairy industries and secondary roads after 1992.

Finally, the contribution of small-scale spontaneous colonisation to deforestation increased from 4 to 10% during the second period. Most of this land use is located on marginal non-flat areas, near the villages and secondary roads. In the second period, the development of the dairy factories and the proximity to deforested areas become critical locational factors of such deforestation process.

7. Factors of deforestation and policy implications

7.1. Do colonisation projects lead to specific land use and deforestation process?

Across the two periods examined, deforestation tends to be located within the colonisation projects zones: 44% of deforestation between 1986 and 1992 was located within the colonisation project zones, and 42% for the next period. For the entire study area,

Table 7
Are and proportion of total deforestation for the considered zones

Zone	Total area (km^2)	Deforestation	
		First period 1986–1992 km^2 (%)	Second period 1992–1999 km^2 (%)
Directed colonisation	5,558.6	972.8 (44.7)	1,775.1 (41.0)
Small-scale spontaneous colonisation	3,461.5	90.2 (4.1)	437.1 (10.1)
Medium-scale spontaneous colonisation	2,617.8	458.2 (21.1)	441.4 (10.2)
Large-scale *fazenda*	9,128.3	650.3 (29.9)	1,637.8 (37.9)

Table 8
Estimates for the Multinomial Logistic Regression model predicting the probability of deforestation for the considered types of farmers, for the first period (1986–1992)

Type	Variables	β	S.E. (β)	Wald χ^2	Significance
(1) Directed colonization	Presence of relief	−0.4284	0.0693	38.17	<0.0001
	Presence of reserve	−1.7625	1.0115	3.03	0.0814
	Presence of colonization zone	9.7616	2.3211	17.68	<0.0001
	Distance from main road	−0.0046	0.0029	2.57	0.0108
	Distance from secondary road	−0.0039	0.0065	11.35	0.0552
	Distance from town	−0.0162	0.0105	12.38	0.1224
	Distance from village	0.0024	0.0026	0.85	0.0355
	Distance from dairy industry	−0.0100	0.0089	12.25	0.0261
	Within counties	0.2518	0.0789	10.17	0.0014
	Distance from forest edge	−0.7445	0.0430	199.51	<0.0001
(2) Small-scale spontaneous colonization	Presence of relief	0.7824	0.1603	23.80	<0.0001
	Presence of reserve	−0.2944	0.2403	1.50	0.2225
	Presence of colonization zone	−6.6483	4.6996	2.00	0.1572
	Distance from main road	0.0901	0.0293	9.48	0.0021
	Distance from secondary road	−0.1569	0.0140	126.07	<0.0001
	Distance from town	−0.0525	0.0291	3.26	0.0708
	Distance from village	−0.1037	0.0103	101.66	<0.0001
	Distance from dairy industry	0.0070	0.0042	2.72	0.0985
	Within counties	0.0193	0.4640	0.01	0.9668
	Distance from forest edge	−0.0788	0.0341	5.32	0.0211
(3) Medium-scale spontaneous colonization	Presence of relief	−0.7563	0.0848	79.58	<0.0001
	Presence of reserve	−2.8843	0.4181	47.59	<0.0001
	Presence of colonization zone	−3.3028	0.1301	444.68	<0.0001
	Distance from main road	−0.0391	0.0046	73.23	<0.0001
	Distance from secondary road	0.0058	0.0034	2.84	0.0917
	Distance from town	−0.0186	0.0024	61.23	<0.0001
	Distance from village	0.0164	0.0037	19.20	<0.0001
	Distance from dairy industry	−0.0316	0.0014	50.22	<0.0001
	Within counties	7.2621	2.5025	8.42	0.0037
	Distance from forest edge	−0.2068	0.0197	110.00	<0.0001
(4) Large-scale fazenda	Presence of relief	−0.3078	0.0742	170.21	<0.0001
	Presence of reserve	−2.2743	0.2039	18.49	<0.0001
	Presence of colonization zone	−4.3925	0.3098	201.05	<0.0001
	Distance from main road	−0.1425	0.0065	188.24	<0.0001
	Distance from secondary road	0.0113	0.0110	1.04	0.3059
	Distance from town	0.0129	0.0035	8.25	0.0007
	Distance from village	0.0736	0.0068	15.10	<0.0001
	Distance from dairy industry	−0.0020	0.0004	2.62	<0.0001
	Within counties	1.6604	0.3834	18.75	<0.0001
	Distance from forest edge	−0.0200	0.0038	26.92	<0.0001

one observes an increase by a factor two of the mean size of the deforestation areas, which results from the creation of larger pasture areas either in huge *fazendas* or in medium-size exploitation issued from the land concentration. But within the colonisation project zones, the mean size of deforested areas was four times higher in the second period, which results from the extension of existing pasture leading to a quasi-continuum of pasture with isolated remaining forest blocks. However, field information suggests that, within the INCRA colonisation zone, this expansion is due to the extension of pasture area within existing properties: the land concentration process is not important because of the uncertainty regarding

Table 9
Estimates for the Multinomial Logistic Regression model predicting the probability of deforestation for the considered types of farmers, for the second period (1992–1999)

Type	Variables	β	S.E. (β)	Wald χ^2	Significance
(1) Directed colonization	Presence of relief	−0.5081	0.0519	96.90	<0.0001
	Presence of reserve	−2.2232	0.5109	18.93	<0.0001
	Presence of colonization zone	11.5790	2.3836	23.59	<0.0001
	Distance from main road	−0.0267	0.0023	130.16	<0.0001
	Distance from secondary road	−0.0678	0.0087	90.63	<0.0001
	Distance from town	−0.0157	0.0029	30.05	<0.0001
	Distance from village	−0.0133	0.0017	59.21	<0.0001
	Distance from dairy industry	0.0304	0.0032	20.39	<0.0001
	Within counties	0.0143	0.0653	0.04	0.8264
	Distance from forest edge	−1.2092	0.0436	626.14	<0.0001
(2) Small-scale spontaneous colonization	Presence of relief	0.9701	0.0665	212.97	<0.0001
	Presence of reserve	−1.0069	0.1128	79.61	<0.0001
	Presence of colonization zone	−0.6504	0.0784	68.82	<0.0001
	Distance from main road	0.1296	0.0124	62.95	<0.0001
	Distance from secondary road	−0.1022	0.0091	125.84	<0.0001
	Distance from town	−0.1077	0.0124	57.79	<0.0001
	Distance from village	−0.0643	0.0051	156.20	<0.0001
	Distance from dairy industry	−0.0876	0.0046	357.55	<0.0001
	Within counties	1.4661	0.1378	113.27	<0.0001
	Distance from forest edge	−0.7403	0.0394	353.23	<0.0001
(3) Medium-scale spontaneous colonization	Presence of relief	−0.1190	0.0425	79.42	<0.0001
	Presence of reserve	−2.6313	0.0986	71.27	<0.0001
	Presence of colonization zone	−1.6117	0.0552	85.15	<0.0001
	Distance from main road	0.0097	0.0026	1.31	0.0023
	Distance from secondary road	−0.0297	0.0016	33.86	<0.0001
	Distance from town	0.0271	0.0020	19.05	<0.0001
	Distance from village	−0.0274	0.0016	28.45	<0.0001
	Distance from dairy industry	−0.0182	0.0016	12.71	<0.0001
	Within counties	0.9786	0.1033	8.95	<0.0001
	Distance from forest edge	−0.3475	0.0138	63.41	<0.0001
(4) Large-scale fazenda	Presence of relief	−0.144	0.0789	4.88	0.0271
	Presence of reserve	−2.37002	0.3546	37.25	<0.0001
	Presence of colonization zone	−2.2124	0.1208	304.02	<0.0001
	Distance from main road	0.0162	0.0130	1.55	0.2130
	Distance from secondary road	−0.1264	0.0053	569.12	<0.0001
	Distance from town	0.0328	0.0054	36.40	<0.0001
	Distance from village	−0.1559	0.0178	76.34	<0.0001
	Distance from dairy industry	0.0138	0.0019	23.10	<0.0001
	Within counties	0.5543	0.3230	2.94	0.0862
	Distance from forest edge	−1.7534	0.1046	280.94	<0.0001

future land titling (potential expropriation by INCRA for properties larger than 100 ha). Very few large cattle ranches are found inside the project zones. It seems that, within the INCRA project, farmers who are willing to expand their properties either move to more remote areas, such as *Iriri*, or continue to work more intensively in their properties and buy remote forest areas for their families. Even if it is too early to conclude, especially because land titling in the colonisation projects is not yet finalised, and therefore not secured, it appears that securing land tenure seems to be not sufficient to reduce pasture expansion or promote forest conservation inside the property. *These colonisation projects therefore offer an opportunity* *for poor landless people to acquire land and access to credit, and seem to reasonably protect them from land concentration. However, they do not limit deforestation, both within or outside their limits.*

7.2. What about the efficiency of the reserve areas?

Approximately 6% of deforestation, for the two periods, was located within reserve areas. Between 1989 and 1992, most of the deforestation within reserves (75%) was located within the indigenous reserve close to the colonisation projects or roads (the *Xikrin* indigenous reserve area[8]). Inversely, for the period 1992–1999, deforestation tends to be located far from the main road network, in other indigenous reserves, and also in natural resources protected areas (the *Tapirape* conservation areas and the *Apyterewa* indigenous reserve). This corresponds to small clearings along existing logging trails, and within some INCRA colonisation zones that were erroneously implemented within those reserves (*Saõ Fransisco* and *Lindoeste* projects).

Since 1998, INCRA has allocated incentives to relocate those farmers outside the reserve area. The slight increase of deforestation in the southern border of the *Apyterewa* indigenous reserve is due to its temporary legal status, ongoing process of regularisation and therefore poorly recognised constraints. *Event though the improved accessibility has resulted in increased pressure on forest reserves, it seems that the conservation areas are reasonably well preserved from deforestation.* This seems not to be true for the case of forest degradation, since logging exploitation has affected all forests in the study area, both within and outside the forest reserves.

7.3. How does pressure on land affect marginal areas?

Deforestation trends during the second period compared to the first also show an increase of deforestation within mountainous areas (approximately 10% increase), mostly for small-scale clearings. When one looks at deforestation rates around the reserves and mountainous areas, the results show an increase of the pressure on these remote and/or marginalized areas. This has been done by computing buffer zones from the considered landscape features. The occurrence of deforestation during the second period is two times higher in areas close to the reserves or mountainous areas. *The increasing population, the development of road network, the creation of new colonisation zones and the resulting pressure on land makes remote and marginalized areas more attractive for migrants* (either from areas affected by land concentration or new migrants from other states). *This is specifically true for small-scale farmers*, who took advantage of the tracks created by loggers into forest areas, sometimes under protected regulation.

7.4. The road issue

Road construction in forested areas unambiguously increases the incentives to convert them to other uses by offering improved marketing opportunities and lowering the cost of migration, access and land clearing (either for productive or speculative purposes). Indeed, the development and improvement of transportation infrastructure tends to be one of the most effective policy tools for influencing the spatial distribution of agricultural and forestry activities. *But the role and impact of roads will depend on the type of road, the stage of development of the frontier area, and roads will affect the various types of producers in different ways.* The main road seems to influence the first step of the colonisation process, while more recent clearings tend to be associated with the emerging secondary road network: the main road acting as an access to the increasing demand from remote markets. Moreover, road development seems important to explaining deforestation processes due to small-scale colonisation, but less significant for large-scale deforestation (*fazendas*). Indeed, this underlines again a specificity of the livestock sector in comparison with other agricultural sectors, i.e. transport is not a significant constraint for large-scale cattle ranching.

8. Conclusion

The emergence of these livestock commodity chains explains: (i) the presence of inter-dependent

[8] Schmink and Wood (1992) relates the particularly turbulent history of the road building to São Félix do Xingú, particularly in relation to the demarcation of the nearby Xikrin indigenous reserve and its potential impacts.

small and large producers in a regional system of meat production and marketing; (ii) the presence of farmers in remote and isolated areas, but still economically profitable for retailers thanks to the high demand which is not constrained by distance; (iii) the pasture monoculture, thanks to the income stability from livestock activities, and the low risk for the farmers' strategy; and (iv) land speculation, because access to land guarantees the link with the existing commercial circuits. All these factors are determinants of a rapid increase in forest conversion for pasture development.

The evolution of these livestock commodity chains has promoted marketing networks, which have greatly influenced the land cover/land use change processes. The forest conversion dynamics, the land speculation, the complementarities among numerous types of actors, the extensification/intensification processes, and the various land use forms are all related to a certain extent to the organisation and development of these commodities chains. The comparative advantage of the Amazon for cattle ranching (as compared to other Brazilian regions) is exploited by these networks, which, provided a minimum infrastructure, has succeeded to provide meat and dairy products to national markets from several Amazonian regions. Remote and marginalized forest areas such as those located around São Félix do Xingú are becoming integrated and competitive within the domestic markets. This relationship between territories and livestock sector shows how much intervention within the livestock sector can contribute to sustainable regional development and land management, and therefore to the limitation of its environmental impacts. Within rapidly evolving frontier areas, even though they are characterised by insecurity and remoteness, the livestock sector has created such a favourable context that the region is becoming organised around livestock-related activities. This goes beyond the land use, affecting political, social, economic and institutional development of the region.

The combination of spatial analysis and livestock commodity chains studies provides an original approach to understanding the land use dynamics within a frontier areas in the Brazilian Amazon. Land use change analyses based on remote sensing give a vision of the regional construction. Moreover, landscape indicators, based on the dominant land use change patterns, can be used to elaborate a typology of the main types of producers and the associated deforestation processes. Spatial statistical models improve the description and characterisation of these deforestation processes. The spatial statistical models have highlighted the fact that explanatory variables, such as the access to markets or the proximity from the roads, influence deforestation in different ways depending on the time period and the type of producers considered. The methodology developed is particularly appropriate for such rapidly evolving agricultural frontiers, because of the richness of satellite remote sensing images, field surveys and extensive data collection from multiple sources.

These models alone are also not well suited for studying the effects of producers characteristics, underlying variables, or less location-specific decision parameters, such as prices. But the increasing availability of geo-referenced and the potential linkages with other sources of socio-economic data may partially overcome this constraint. Following these first results, it is now easier to identify particular questions that have to be addressed to specific actors to better distinguish correlation from causality. Research projects are currently undertaken by our team to survey farmers strategies and constraints at the property level. All the data collected should be integrated in economic models (dynamic simulation) that will analyse several scenarios for regional development and deforestation in these regions. Thus, by identifying particular relationships between the location and extent of deforestation, types of producers and their economic environment, such models can further be used at local and regional-scale as tools to guide policies that can potentially affect deforestation, such as infrastructure, land tenure, conservation policies.

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