Global Change Biology (2004) **10**, 745–764, doi: 10.1111/j.1529-8817.2003.00769.x

Simulating the response of land-cover changes to road paving and governance along a major Amazon highway: the Santarém–Cuiabá corridor

BRITALDO SOARES-FILHO*†, ANE ALENCAR‡, DANIEL NEPSTAD‡§, GUSTAVO CERQUEIRA*, MARIA DEL CARMEN VERA DIAZ‡, SÉRGIO RIVERO‡, LUIS SOLÓRZANO§ and ELIANE VOLL*

**Centro de Sensoriamento Remoto, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, Belo Horizonte 31270-900, MG, Brazil, †Centro de Desenvolvimento e Planejamento Regional, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, Belo Horizonte 31270-900, MG, Brazil, ‡Instituto de Pesquisa Ambiental da Amazônia, Av. Nazaré 669, 66035-170 Belém, Pará, Brazil, §The Woods Hole Research Center, Woods Hole, MA 02543-0296, USA*

Abstract

The spatial distribution of human activities in forest frontier regions is strongly influenced by transportation infrastructure. With the planned paving of 6000 km of highway in the Amazon Basin, agricultural frontier expansion will follow, triggering potentially large changes in the location and rate of deforestation. We developed a land-cover change simulation model that is responsive to road paving and policy intervention scenarios for the BR-163 highway in central Amazonia. This corridor links the cities of Cuiabá, in central Brazil, and Santarém, on the southern margin of the Amazon River. It connects important soybean production regions and burgeoning population centers in Mato Grosso State with the international port of Santarém, but 1000 km of this road are still not paved. It is within this context that the Brazilian government has prioritized the paving of this road to turn it into a major soybean exportation facility. The model assesses the impacts of this road paving within four scenarios: two population scenarios (high and moderate growth) and two policy intervention scenarios. In the 'business-as-usual' policy scenario, the responses of deforestation and land abandonment to road paving are estimated based on historical rates of Amazon regions that had a major road paved. In the 'governance' scenario, several plausible improvements in the enforcement of environmental regulations, support for sustainable land-use systems, and local institutional capacity are invoked to modify the historical rates. Model inputs include data collected during expeditions and through participatory mapping exercises conducted with agents from four major frontier types along the road. The model has two components. A scenario-generating submodel is coupled to a landscape dynamics simulator, 'DINAMICA', which spatially allocates the land-cover transitions using a GIS database. The model was run for 30 years, divided into annual time steps. It predicted more than twice as much deforestation along the corridor in business-as-usual vs. governance scenarios. The model demonstrates how field data gathered along a 1000 km corridor can be used to develop plausible scenarios of future land-cover change trajectories that are relevant to both global change science and the decision-making process of governments and civil society in an important rainforest region.

Keywords: Amazon, land-cover change, policy intervention scenario, simulation model

Received 23 June 2003; revised version received 6 August 2003

Correspondence: Britaldo Soares-Filho, Centro de Sensoriamento Remoto, e-mail: britaldo@csr.ufmg.br

Introduction

Industrial activity and large-scale changes in land cover and land use are provoking vast changes in the planet (Turner II *et al*., 1994), among which the rapid loss of tropical forest, particularly in Amazonia, is of great concern. Tropical forests are responsible for one-fourth of the world's primary productivity and more than half of the world's plant and animal species. The expansion of agricultural and urban frontiers in tropical forest regions releases approximately one-fourth of the world's global human-induced carbon emissions to the atmosphere (Houghton, 1999). The primary determinant of the spatial distribution and, perhaps, the rate of forest clearing is access. Forests are logged and converted to agriculture, plantations, and cattle pastures where roads and rivers provide easy access.

The world's main program of road expansion into tropical forests is in the Brazilian Amazon, where 6000 km of highway are slated for paving by the Brazilian government (Nepstad *et al.*, 2000, 2001; Carvalho *et al.*, 2001). Deforestation in the Brazilian Amazonia has accelerated during the last decade (Laurance *et al.*, 2001; INPE, 2002) and may increase further as the Brazilian Government implements its development plan, which features extensive road paving, river channelization, port construction, and new hydroelectric plants through the Amazonian region (Nepstad *et al.*, 2000, 2001; Carvalho *et al.*, 2001).

To understand the complex interactions among human and biophysical factors that drive the expansion of tropical deforestation, numerous models of tropical deforestation have been developed. Kaimowitz & Angelsen (1998) provide a detailed review of these models, to which can be added Pfaff (1999), Messina & Wash (2000), Mertens & Lambin (2000), Nepstad *et al.* (2001), Laurance *et al.* (2001), Soares-Filho *et al.* (2001), Soares-Filho *et al.* (2002a), Alves (2002a, b), and Geist & Lambin (2002). Previous efforts to simulate the effects of road paving on land-use change in the tropics have employed analyses of historical patterns of land clearing within incremental buffers along roads (e.g. Nepstad *et al.*, 2000, 2001; Laurance *et al.*, 2001), spatial logistic regression (e.g. Mertens & Lambin, 1997; Nelson *et al.*, 1999; Soares-Filho *et al.*, 2001) and econometric analysis (e.g. Reis & Guzmán, 1994; Chomitz & Gray, 1996). The first approaches are limited by the assumption that future land-use patterns will mimic historical patterns, while the third is limited by data availability and lack of explanatory mechanisms. Furthermore, none of these previous modeling approaches have explicitly incorporated simulation devices to reproduce the spatial patterns of change and the response of land-cover change to policy intervention scenarios.

We have developed a spatially explicit simulation model that is responsive to policy intervention scenarios for the BR-163 corridor in central Amazonia, focusing on the role of governance in directing land-cover change. We define governance to include the actions by the State and civil society that protect public interests in natural resources and their utilization, including regulation, law enforcement, fiscal incentives, and the organization of informal networks of rural producers (Carvalho *et al.*, 2001; Nepstad *et al.*, 2002).

The BR-163 road links the cities of Cuiabá, in central Brazil, and Santarém, on the southern margin of the Amazon River (Fig. 1). It connects burgeoning soybean

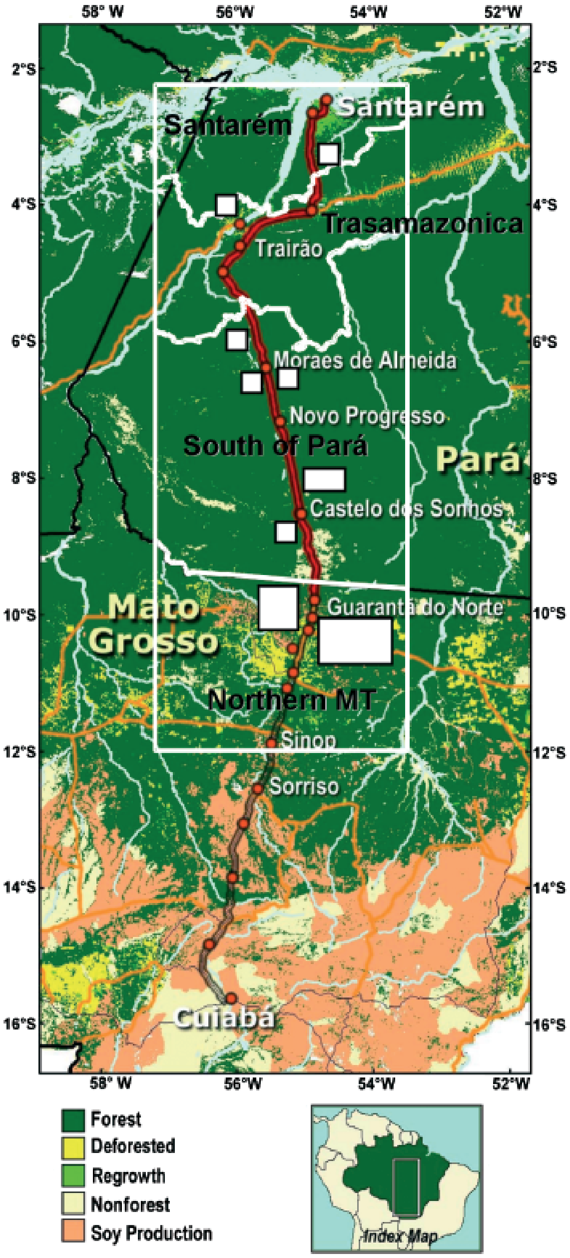

Fig. 1 The study area and its location with respect to Brazilian Amazon. The region comprised by the simulation and its subregions are contoured with white lines; the case study areas are marked with small rectangles.

production regions and population centers in Mato Grosso State with the international port of Santarém. But 1000 km of this road is still not paved. Moreover, it crosses large tracts of undisturbed forest in Pará state, a land coveted by loggers, land speculators, farmers, and ranchers. Due to its strategic position, the Brazilian government has prioritized the paving of this road to turn it into a major soybean exportation facility (Carvalho *et al*., 2001; Nepstad *et al*., 2002). We therefore employ our simulation model to assess the potential of policy interventions to diminish the indirect effects of the paving of this major Amazon highway on deforestation.

The study region and its frontiers

To perform the simulations, we defined a corridor of 410 × 1080 km, centered on the unpaved portion of the BR-163 road. We divided the corridor into four subregions, based upon the portion of the forest already cleared, and the major economic activities (mechanized agriculture, small landholder agriculture, incipient cattle ranching, and logging). These subregions are: (a) Northern Mato Grosso, the most consolidated frontier, dominated by agribusiness and ranching; (b) South of Pará, the wild core area, a young extraction frontier with high deforestation potential; (c) the Transamazonica region, a 30-year-old settlement region, considered to be a transitional small landholder frontier; and (d) Santarém, the oldest colonization region that represents an urbanized-transitional small landholder frontier (Figs 1 and 2). These regions differ not only by their particular histories of occupation but also agrarian structures, population density, urbanization level (percent of the population living in towns and cities), and current landscape dynamics. During the last decade, the South of Pará frontier had the lowest population density but the highest population growth rate (Table 1), indicating a strong influx of immigrants. This young frontier still has the largest proportion of intact forest and the lowest rates of deforestation (Table 2). The Transamazonica and Santarém regions, in turn, show an agrarian structure dominated by small landholders (properties <200 ha) distributed in several settlement projects, similar intermediate deforestation rates and high population growth rates with low urbanization growth rates. The largest share of the BR-163 population is found in the Santarém region, where the city of Santarém alone has over 186 000 people. Northern Mato Grosso presents the second highest population along the BR-163, and is even more urbanized (72%) than Santarém (65%). Northern Mato Grosso is also distinctive because of its strong agrarian concentration (84% of the land is in properties of 200 ha and greater), large proportion of deforested land, and high deforestation rate (Tables 1 and 2).

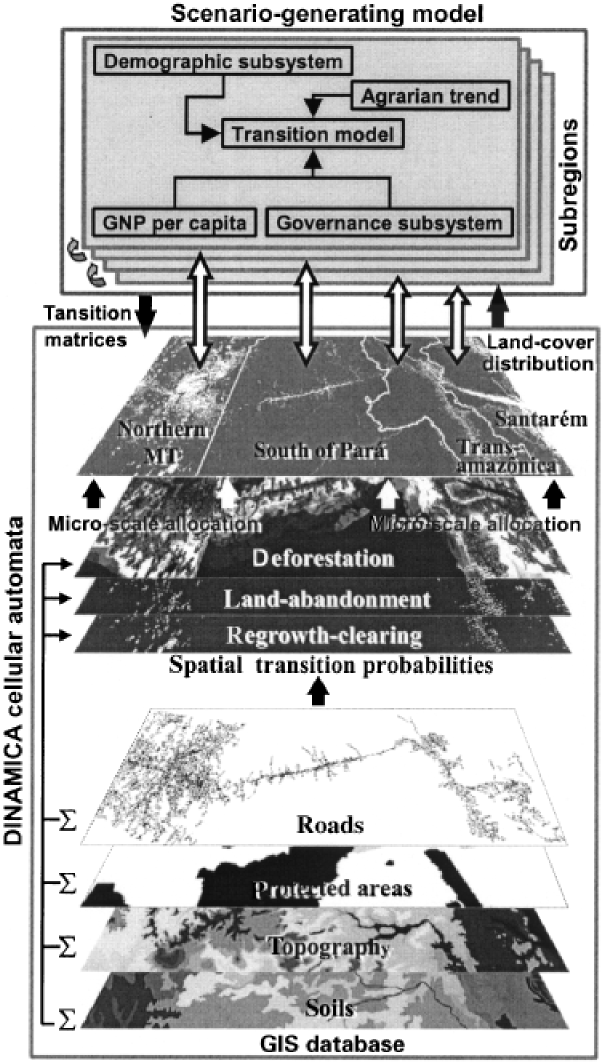

Fig. 2 Linkage between the scenario-generating model and DINAMICA. DINAMICA receives the transition matrices output by the upper scenario model (one for each subregion) and returns to it the land-cover distribution of each subregion. DINAMICA allocates the changes using transition probability maps calculated by integrating the weights of evidence of spatial variables.

The alternative scenarios

An important challenge to global science is to simulate the influence of potential policy interventions on the processes that are impoverishing native ecosystems. The model is therefore designed to assess the responses of land-cover change to road paving across a range of demographic and policy scenarios. We present here model outputs for two population scenarios – high and

Table 1 Population and agrarian structure data for the subregions

	Northern MT	South of Pará	Transamazonica	Santarém
1991				
Urban population	182 104	0	71 853	229 728
Rural population	120 151	40 667	77 233	117 620
Total population	302 255	40 667	149 086	347 348
Urbanization (%)	60.3	–	48.2	66.1
1996				
Urban population	204 766	3667	76 528	240 081
Rural population	111 999	51 211	87 960	123 114
Total population	316 765	54 878	164 488	363 195
Urbanization (%)	64.6	6.7	46.5	66.1
2000				
Urban population	258 342	9580	92 536	261 912
Rural population	102 061	47 418	96 571	143 528
Total population	360 403	56 998	189 107	405 440
Urbanization (%)	71.7	16.8	48.9	64.6
1991/1996				
Annual population growth rate	0.0094	0.0618	0.0199	0.0090
Annual urbanization rate	0.0142	0.0020	−0.0068	−0.0001
1996/2000				
Annual population growth rate	0.0209	0.0076	0.0284	0.0223
Annual urbanization rate	0.0262	0.1007	0.0102	−0.0045
1991/2000				
Annual population growth rate	0.0197	0.0382	0.0268	0.0173
Annual urbanization. rate	0.0195	0.1113	0.0017	−0.0026
% of land in 1996				
<200 ha	16.2	32.6	75.6	72.9
≥ 200 ha	83.8	67.4	24.4	27.1

Agricultural census of 1996, census of 1991 and 2000, and 1996 population tallied by IBGE (1991, 1996a, b, 2000).

Table 2 Land-cover data for the subregions derived from TRFIC 1992 to 1996 forest-cover maps

	1992's forest cover map km^2				1996's forest cover map km^2			
	Northern MT	South of Pará	Transamaz.	Santarém	Northern MT	South of Pará	Transamaz.	Santarém
Forest	95 135	176 412	73 993	51 998	88 081	174 668	72 507	51 163
Deforested	14 985	1256	2072	1337	17 739	2085	1997	1086
Regrowth	2272	198	1966	3795	6426	460	3358	4146
Water/clouds	836	630	1061	7075	982	1283	1230	7810
Total	113 228	178 496	79 092	64 205	113 228	178 496	79 092	64 205
Subregion area	114 223	181 712	80 936	65 918	114 223	181 712	80 936	65 918
1992–1996 annual deforestation rate					0.0191	0.0025	0.0051	0.0040
Annual land-abandonment rate					0.0391	0.1307	0.1568	0.1830
Annual regrowth clearing rate					0.2281	0.1598	0.1438	0.1438
1996's overall deforested land (deforested + regrowth) km^2					24 165	2545	5355	5232
BR-163 road length through subregion (km)					277	472	233	136
Extend of deforested land divided by road length (km)					87.21	5.39	22.95	38.42

Land-abandonment and regrowth clearing rates are derived from case studies.
The difference between the total and subregion area is due to different cartographic methods of area measurement, the first using the average pixel size and the latter the subregion's vector polygon. TRFIC, Tropical Rain Forest Information Center.

moderate growth – vs. two contrasting policy intervention scenarios. At one extreme, we assume a business-as-usual scenario, based on historical patterns of law enforcement, agricultural credit, agricultural extension, social organization and investments, and agrarian trends. At the other extreme, we assume a scenario of high governance, in which road paving is accompanied by recent advances in the enforcement of environmental regulation, land-use planning by local governments, support for sustainable land-use systems, and participation of organized civil society (Carvalho *et al.*, 2001; Nepstad, *et al.*, 2002).

We selected parameters to use in the governance scenarios and assigned the effects of these parameters qualitatively on land-cover changes based on a review of the literature and extensive field surveys along the Cuiabá–Santarém highway. Field work along the highway began with an 11-day expedition from Santarém to Cuiabá in October of 2000, during which we spent a day in each of the major towns and cities, interviewing representatives of farming, logging, commerce and local government about the likely consequences of road paving, and means of mitigating negative consequences. This initial survey was supplemented by participatory workshops held in each of nine cities and towns, involving a total of more than 200 participants, from March to September of 2001. During these workshops, we were able to identify the most likely consequences of road paving from the viewpoint of local actors, and the most important policy interventions that might help to avoid negative consequences.

Combining the results of field work with a critical review of the literature, we identified several processes that drive deforestation in the Amazon, and that could be changed in a high governance scenario. Deforestation in the Amazon has been accelerated in the past by fiscal policies that favor large-scale forest conversion to extensive, low grazing density cattle pastures (Hecht *et al.*, 1988; Mahar, 1988), by land tenure policies in which forest conversion to cattle pasture is the cheapest way of demonstrating land 'improvement' (Fearnside, 1985; Mahar, 1988), and by land tenure conflicts in which land owners assert their control over land by clearing it (Schmink & Wood, 1992). One of the barriers to the adoption of potentially permanent production systems, such as perennial crops and forest management, in the place of the region's dominant deforestation-dependent land-use systems (swidden agriculture and extensive cattle pasture) is the lack of agricultural extension services, inadequate agricultural credit systems, poor maintenance of secondary roads, and the fear of losing agricultural and forestry investments through land conflict, invasion by squatters, and accidental fire (Schmink & Wood, 1992; Nepstad *et al.*, 1999a; Alston *et al.*, 2000; Fearnside, 2001).

The results of this analysis can be summarized as the following set of assumptions:

1. Landholders clear their forest less if:
   a. they have strong claims on their property (legal titles);
   b. they are provided with access to credit and technical assistance in support of sustainable intensive land-use systems, such as perennial crops, annual crops within an intensified fallow management system, intensive cattle production – high grazing density (Mattos & Uhl, 1994) – on improved pastures and forest management;
   c. land-use regulations are enforced by IBAMA (the federal environmental enforcement agency), restricting the percentage of their properties that they can clear;
   d. they have access to basic services (health care, schools, police services, justice), making the prospect of long-term residence in a region more attractive;
   e. they are organized in cooperatives and associations.
2. Forest conversion to pasture and agricultural fields is also suppressed locally by:
   a. protecting indigenous reserves and protected areas from invasion by ranchers and farmers;
   b. avoiding the settlement of small landholder colonists in forested landscapes that are not already occupied;
   c. implementing deforestation and fire licensing systems; and
   d. reducing land speculation (*grilagem*) by nullifying illegal land titles.

Every one of these assumptions is explicitly or implicitly stated in Brazilian laws and policies for the Amazon, and several of these ambitious measures of Amazon 'frontier governance' have been implemented (Nepstad *et al.*, 2002), at least temporarily. These institutional and policy assumptions are represented as several discrete variables, summarized in Table 3. We call the organization of civil society 'social capital' (Putnam *et al.*, 1992) and measure it by the number and effectiveness of unions/associations and other nongovernmental organizations. 'Federal Government' variables include the presence of IBAMA (the federal environmental enforcement agency), implementation of conservation units, effectiveness of FUNAI (the federal indigenous group agency) in protecting indigenous reserve boundaries, the role of INCRA (the

Table 3 Scenario variables lookup table for the BR-163 simulation model, showing their trends of increase and influences on the modeled transitions

				Influences on the modeled transitions											
				Deforestation				Land-abandonment				Regrowth clearing			
		Trends of increase		Small landholder		Farmer/ rancher		Small landholder		Farmer/ rancher		Small landholder		Farmer/ rancher	
	Inhibiting and motivating factors	Bu.	Go.	Bu.	Go.	Bu.	Go.	Bu.	Go.	Bu.	Go.	Bu.	Go.	Bu.	Go.
Social capital	Unions and associations	1	3	−1	−1	−1	−1	−1	−1	0	0	0	0	0	0
	NGO	1	3	−1	−1	−1	−1	1	1	0	0	0	0	0	0
Federal government	IBAMA	1	3	−1	−1	−2	−2	0	0	0	0	−1	−1	−1	−1
	Conservation units implementation	1	3	−2	−2	−2	−2	0	0	0	0	0	0	0	0
	FUNAI and indigenous reserves	1	3	−1	−1	−1	−1	0	0	0	0	0	0	0	0
	INCRA (agrarian reform – settlements)	1	3	2	1	1	1	−1	−1	−2	−2	1	1	1	1
	INCRA (title regularization)	1	3	−1	−1	−1	−1	−1	−1	−1	−1	1	1	1	1
	Technical assistance	1	3	−1	−1	−1	−1	−1	−1	−1	−1	1	1	1	1
	Credit	1	3	1	−2	1	0	−1	−1	−1	−1	1	1	1	1
State/local government	Roads and energy	2	3	2	1	2	1	−1	−1	−1	−1	1	1	1	1
	Civil law enforcement	1	3	−1	−1	−2	−2	0	0	0	0	−1	−1	−1	−1
	Health and education	1	3	−1	−1	0	0	−1	−1	−1	−1	1	1	0	0
Agrarian dynamics	Agrarian concentration	3	1	Internally modeled											
Demography	Rural population/growth and migration			Internally modeled											
	Urban population/growth and migration			Internally modeled											
Economy	GNP per capita			Internally modeled											
	Integrated effect			−3	−30	−5	−27	−7	−18	−8	−21	5	12	4	9

Values for trends of increase vary from 0 (no increase) to 3 (large increase). Influences on the modeled transitions vary from −2 (strong negative), to 2 (strong positive). The integrated effect represents the sum of scenario variables' trend of increase multiplied by their influences. Internally modeled variables are those directly processed by the model using either empirical quantitative functions or internal lookup tables described in the text. Bu., business-as-usual; Go., governance scenario.

federal colonization and agrarian reform agency) in establishing and regularizing settlement projects as well as granting land titles to farmers. Support for sustainable agriculture, in the form of technical assistance and credit, is also a federal government variable. 'State and local government' variables include establishment and maintenance of road and energy networks, civil law enforcement, and provision of health and educational services.

Beyond these institutional and policy drivers, demographic change and economic factors are also important determinants of Amazon deforestation and land abandonment. Demography is responsive to government resettlement policies and agricultural policies inside and outside of the Amazon (Skole *et al*., 1994), including rates of in- and out-migration. We divided demography into rural and urban populations and their related migration fluxes (Table 3). Land-cover dynamics are also a function of agrarian concentration, the size of rural properties, as land concentration compels people who lost their lands to move to new frontiers. Land-cover change is also influenced by economic growth, which we represent in the model as the gross national product (GNP) per capita.

The scenario variables represent the inhibiting and motivating factors that influence the selected agent's tendency to deforest his land, to abandon his land, triggering forest regrowth, and to clear secondary vegetation to use his land again. Thus, the landscape transitions modeled are (1) deforestation, (2) land abandonment, and (3) regrowth clearing, and the model employs two types of agents: (1) small landholders and (2) farmers and cattle ranchers combined (Table 3). These agents were chosen based on their prominent role in frontier land-cover change (Reis & Guzmán, 1994; Fearnside, 1996). Although, Fearnside (1996) defines small landholders as those whose properties are equal or less than 100 ha, we used 200 ha as a top limit, by reason of the data stratification from IBGE's statistics (Brazilian Geographical and Statistics Institute). The participatory workshops included both categories of landholders.

Loggers also have a substantial role in impoverishing the forest and pushing forward the frontier (Veríssimo *et al*., 1992; Nepstad *et al*., 1999b). However, logging was not included in the model, because this version only deals with deforestation defined as forest clear-cutting, and not forest thinning that results from selective logging.

GNP per capita, population and urbanization growth, and agrarian dynamics are quantitative variables internally modeled, while the other variables were set according to the local perceptions registered during field surveys. The governance effect is estimated qualitatively by first projecting the trends of the selected variables and then assigning their effects to the land-cover changes driven by the frontier agents.

The influence of the qualitative scenario variables is differentiated by agent type and scenario. For example, regulation enforcement by IBAMA tends to be weaker over small landholders because they are far more numerous than large-scale landholders (and therefore more expensive to regulate), and because strict regulation of some small landholders could threaten their survival. The establishment and maintenance of conservation units are perceived as a strong measure to reduce deforestation as well as the maintenance of the current indigenous reserves by FUNAI, hence these measures should be intensified in the governance scenario. Agrarian reform carried out in the Brazilian Amazon is considered a polemic topic since it produces as a side-effect additional deforestation caused by both small landholders attempting to establish new settlement areas and farmers and ranchers who clear-cut the forest to ensure their land title. This also explains how title regularization through INCRA could reduce deforestation. Although better regional infrastructure (including rural electricity and paving and maintenance of vicinal roads) could facilitate the opening of new deforestation fronts, it also favors land-use intensification on previously deforested land and consequently reduces population mobility towards new frontiers, thus its effect depends on the overall scenario. Better security, health, and education motivate the local people to preserve their natural heritage. Technical assistance reduces deforestation since small landholders, farmers and ranchers will manage better their cultures and pastures, consequently alleviating the need to open up new lands from the forest. Credit is envisaged as an ambiguous variable since it can show opposite effects within each scenario, i.e. it can either lead to further deforestation, as a result of more resources, or stimulate conservation through funding agro-forestry, i.e. green credit.

The increasing trends of the inhibiting and motivating factors were standardized considering the current tendency observed throughout the region as a baseline. In this manner, values for trends of increase vary from 0 (no increase from the current tendency) to 3 (large increase). Influences on the modeled transitions vary from -2 (strong negative influence) to 2 (strong positive influence). The integrated effect of the scenario on a particular land-cover transition is determined by summing the products of each variable's trend of increase by its influence on that transition. Hence, the high governance scenario presented in this paper departs from the business-as-usual scenario by the aggregate factors depicted in the bottom row of Table 3.

Model design and implementation

General approach

The simulation model is composed of two coupled components. At the top, it has a scenario-generating model, named 'alternative scenarios model', which integrates the forces that motivate or inhibit the agent behaviors to change the landscape (Table 3). As output, the scenario-generating model provides dynamic transition matrices, in which the historical transition rates are modified as a function of the integrated effect of scenario variables (Table 3). Each subregion has its own submodel and the submodels communicate among themselves through the flow of people and information. The alternative scenarios model was written using VENSIM, a system thinking software (Ventana, 2002).

The transition matrices output by the upper model are passed on to DINAMICA, a spatially explicit, cellular automata simulation model (Soares-Filho *et al.*, 2002a, b) that allocates the changes across the landscape based on spatial data layers representing physical and political conditions that are stored in a GIS. The upper model therefore establishes the circumstances (scenarios) under which the spatially explicit simulation runs (Fig. 2). As interactions between landscape elements occur in different ways, depending on local characteristics and transition rates, DINAMICA will produce distinct spatial patterns of change.

The alternative scenarios model

As input, this model receives each region's land-cover transition matrix and initial distribution of the land-cover classes: forest, deforested (agriculture and pastures in several stages of use – the dominant land use in the region), and regrowth (including young regrowth and secondary forest in several stages of succession) (Table 2). These data were derived from the forest-cover maps of 1992 and 1996, obtained at full (30 m) resolution from Tropical Rain Forest Information Center (TRFIC). Due to misregistration in these data, land abandonment and regrowth-clearing rates were derived from multitemporal land-use and land-cover maps of selected case study areas, where extensive fieldwork and Landsat image processing had been carried out (see Fig. 1). The historical transition rates are calculated as follows:

$$Rate_{ij} = \frac{n_{ij}}{\sum_{j=1}^{n} n_{ij}}, \tag{1}$$

where n_{ij} is the number of transitions $i \Rightarrow j$ occurred in a time period, i.e. 1992–1996. As the model is set to run in yearly time steps, the time-period rates still need to be converted to annual rates by using the following transformation:

$$P^{1/n} = HV^{1/n}H^{-1}, \tag{2}$$

where $P^{1/n}$ is the annual transition matrix, and H and V are the eigenvector and eigenvalue matrices of the original time-period matrix, and n is the number of years encompassed by the period.

The model for each subregion in the corridor receives: (1) the agrarian structure derived from the agricultural census data of 1996 (IBGE, 1996a), including the percentage of land occupied by cattle ranchers and farmers (properties $\geq$200 ha) and small landholders (properties $<$200 ha), (2) the rural and urban populations from the 1991 and 2000 census and from the 1996 population tallied by IBGE (IBGE, 1991, 1996b, 2000), and (3) the Brazilian GNP and population from 1990 to 2000 (MDIC, 2002) (Table 1).

At the core of the model, each subregion has its own land-cover transition matrix, and the upper scenario model acts upon the transition rates of these matrices, first projecting the trend of a series of variables, and then the effect of these variables on the land-cover change rates for a particular scenario. The transition model is calculated as

$$\begin{bmatrix} \textit{Deforested} \\ \textit{Regrowth} \\ \textit{Forest} \end{bmatrix}_{t=n} = \begin{bmatrix} 1-dr_t & rd_t & fd_t \\ dr_t & 1-rd_t & 0 \\ 0 & 0 & 1-fd_t \end{bmatrix}^n \times \begin{bmatrix} \textit{Deforested} \\ \textit{Regrowth} \\ \textit{Forest} \end{bmatrix}_{t=0}, \tag{3}$$

where dr_t, rd_t, and fd_t are, respectively, the transition rates for land abandonment, regrowth clearing and deforestation and, n the time span in years. The transition matrix multiplies the vector containing the distribution of the landscape classes: *deforested*, *regrowth*, and *forest*. This equation is a not a classical Markovian transition model because the rates are dynamic and also vary within each scenario. The transition rates are either accelerated or slowed down by the model depending on the scenario variables. Hence, a transition rate, at a time $t+n$, represents a departure from the initial annual historical rate, as derived from 1996 to 1992 TRFIC forest-cover maps. The model tracks secondary forest development following abandonment, estimated on the basis of local ecological characteristics (including soil and climate) and the sojourn time (time since abandonment), which is updated by the spatial model for each cell of the output landscape map.

The alternative scenarios model calculates deforestation rate (fd_t), at a time t, as a function of the integrated effect of population, urbanization level, GNP per capita growth, agrarian concentration, remaining forest, governance level, and consequently the agents' inhibition or motivation levels. Its base equation is as follows:

$$fd_t = fd_{t-1} \times def\_saturation_t \times \Delta GNPc_t \times anthropic\_press_t \times \sum_i \frac{area_{i,t} \times agent\_mot_{i,deforestation,t}}{total\_area}. \tag{4}$$

The term *agent_mot* synthesizes the agent motivation to deforest, as explained below in Eqn (9); *total_area* corresponds to the subregion's area, and *area* is the land area occupied by each modeled agent (*i*), namely, (1) small landholders and (2) farmers and cattle ranchers.

The term *def_saturation* is an asymptotic factor that forces the cessation of deforestation when the remaining forest (*forest*) reaches a minimum percentage of the subregion's area (*total_area*). It is calculated by the following equation:

$$def\_saturation_t = \frac{(forest_t - total\_area \times r_{scenario})}{(forest_t + total\_area \times r_{scenario})} \times \frac{(initial\_forest + total\_area \times r_{scenario})}{(initial\_forest - total\_area \times r_{scenario})}, \tag{5}$$

where *initial_forest* is the initial forest extent and *r* is the minimum percentage of remaining forest defined for a certain scenario and agrarian structure, as small landholders tend to deforest more intensively their properties (Fearnside, 1993; Alencar *et al.*, 1997; Soares-Filho, 2001).

$\Delta GNPc$ corresponds to the variation in the deforestation rate attributable to GNP per capita. Growth in GNP per capita speeds up deforestation, as it provides capital that is necessary for the deforestation process. There is a 1 year lag in the response of deforestation to GNP growth, as occurred in 1995, when deforestation surged as a result of the previous year's high GNP growth rate artificially produced by the Brazilian economic plan – *Plano Real* (Fig. 3). Furthermore, deforestation rate seems to have increased during the last decade as a function of GNP per capita of the previous year. This regression is used to derive the numeric coefficients of the following equation (Fig. 4):

$$\Delta GNPc_t = \frac{0.000003 \times GNPc_{t-1} - 0.0111}{0.000003 \times GNPc_{t-2} - 0.0111}, \tag{6}$$

where $GNPc_t$ is the GNP per capita at time *t*. $\Delta GNPc$ greater than one will enhance the anthropic pressure (*anthropic_press*) in Eqn (4); thus, the model assumes that frontier expansion in the Brazilian Amazon during the period simulated by the model falls on the left side of the inverted U-shape Kuznets curve, which describes the relationship between per capita income and environmental degradation (Stern *et al.*, 1996).

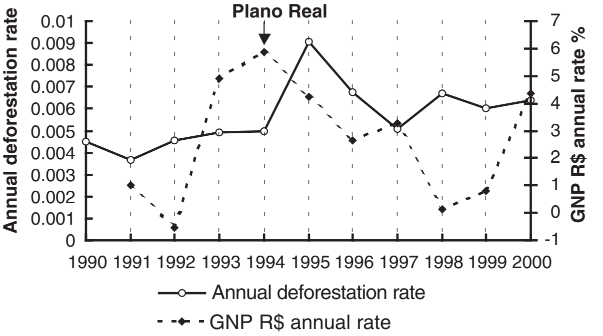

Fig. 3 Annual deforestation rate of Amazonia compared with Brazilian gross national product (GNP) growth rate. Deforestation data are from INPE (2002) and GNP growth rate is obtained from GNP corrected to 2001's Brazilian currency – *Reais* (MDIC, 2002).

The anthropic pressure (*anthropic_press*) is a ratio between the 'expected' density of deforested land (deforested land/subregion's area) for a given rural demographic density and agrarian structure, and the current density of deforested land. Values above one mean that the pressure is higher than it would be expected, hence pressing the deforestation rate upwards. The anthropic pressure, at a time *t*, is given by

$$anthropic\_press_t = \left(\frac{density\_of\_deforested\_from\_pop_t}{density\_of\_deforested_t} - 1\right) \times acc\_factor + 1, \tag{7}$$

where *density_of_deforested* is the current area of deforested land divided by the subregion's area. Defined by a lookup table, the acceleration factor (*acc_factor*) is a parameter used by the scenario-generating model to impose a delay in adjusting the anthropic pressure in response to the current demographic density. The acceleration factor is used to gradually release the demographic pressure caused by the paving of the Cuiabá–Santarém road. In this manner, it starts rising at the year 2003 and reaches a plateau at 2020 (Fig. 5a). The term *density_of_deforested_from_pop* (theoretical density of deforested land as a function of rural population density) is obtained empirically.

Surrounding the subregions' transition models (Eqn (3)) are demographic dynamics subsystems that project the population growth and its urbanization level for the subregions (Fig. 6). Population dynamics are linked to the deforestation rate by the term *density_of_deforested_from_pop* that is calculated based on the current rural population density (*rural_population_density*), using the empirical relationship determined by the analysis of

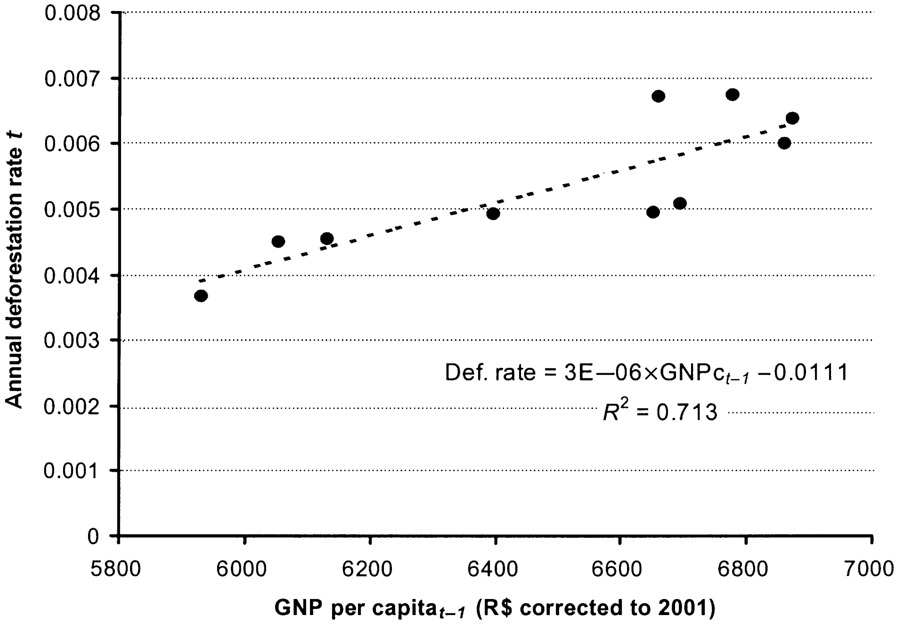

Fig. 4 Regression analysis of annual deforestation rates of Amazonia vs. gross national product (GNP) per capita at time = $t-1$. Deforestation rates derived from INPE (2002). GNP per capita in *Reais* corrected for 2001 (MDIC, 2002). 1995's deforestation rate was considered an outlier and thereof excluded.

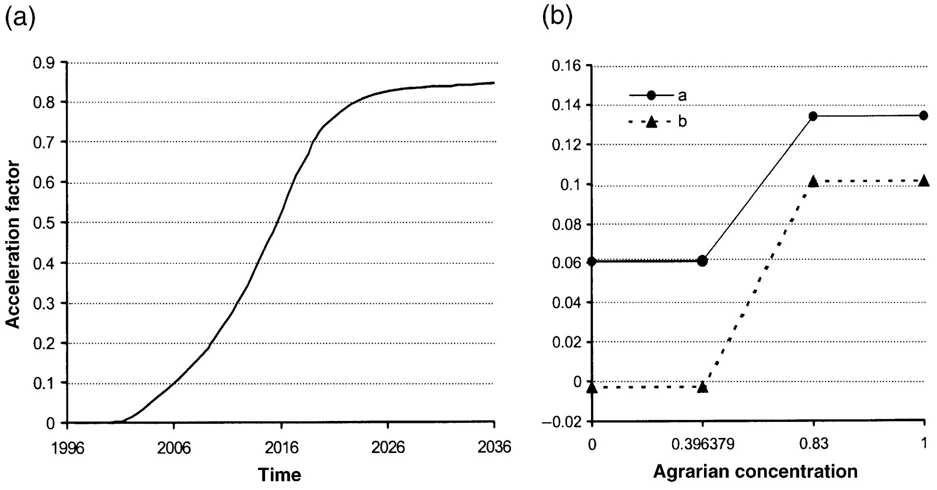

Fig. 5 Lookup tables of the acceleration factor (*acc_factor*) in Eqns (7) and (9) (a), and the coefficients *a* and *b*, in Eqn (8), as a function of agrarian concentration (b). Agrarian concentration equal to 1 means that the region is devoid of small landholders.

municipality data along the BR-163 corridor (Fig. 7):

$$\begin{aligned} &density\_of\_deforested\_from\_pop_t \\ &\quad = a_{scenario,t} \times rural\_population\_density_{scenario,t} + b_{scenario,t} \end{aligned} \tag{8}$$

The sole use of rural population does not imply that the model ignores the influence of urban centers, as it considers that strong urbanization reduces deforestation. The influence of the rural population density on deforestation depends on the region's agrarian structure, being stronger in areas where the land is concentrated among few property holders. This assertion is pointed out by the steeper regression slope obtained from the Northern Mato Grosso municipality data, where farmers with properties over 200 ha hold

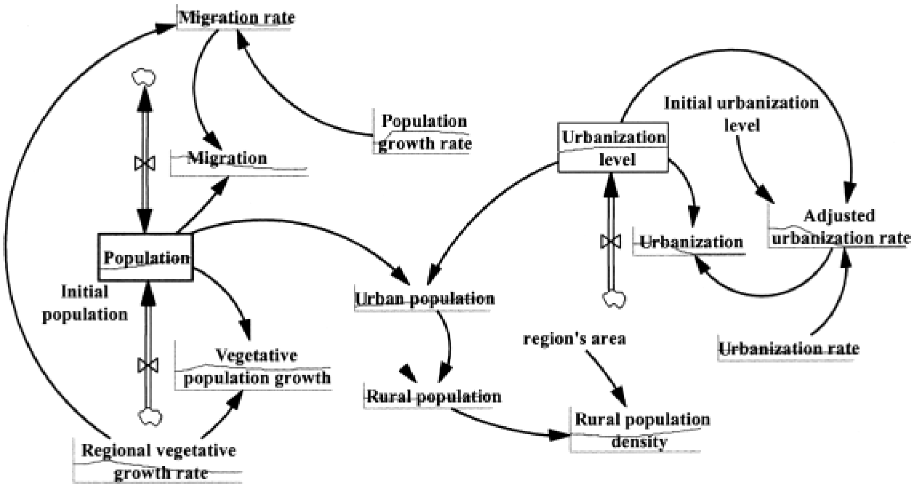

Fig. 6 Demographic dynamics subsystem. Population is a function of growth and migration rates. Birth and death functions are included in the inflows and outflows (double arrow). Migration rates is estimated considering the difference between the subregion's growth rate and the regional vegetative growth rate. Urbanization and population growth rates are defined by lookup tables. The subsystem is fed with data from IBGE's census.

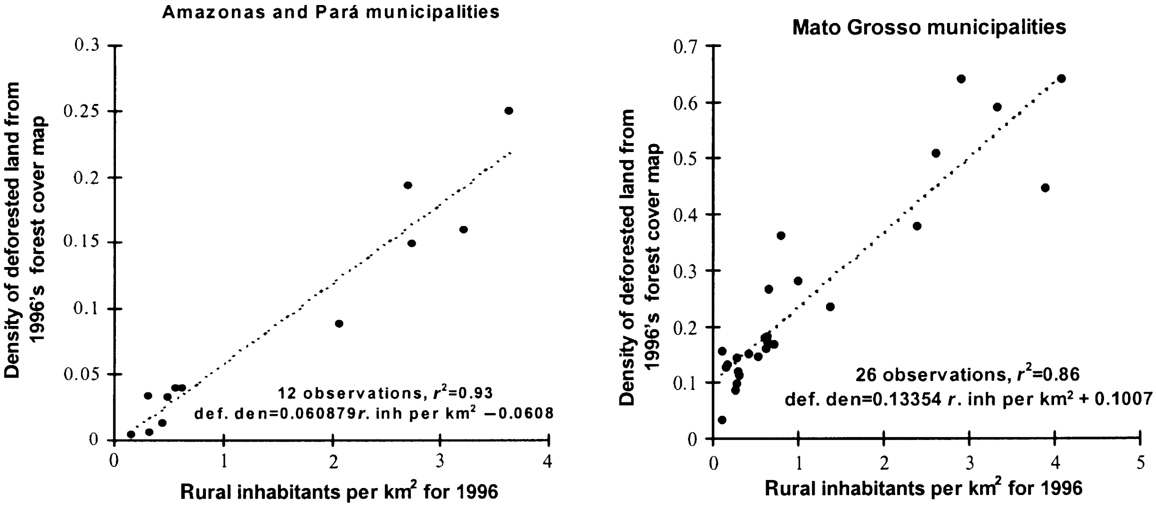

Fig. 7 Results of regression analyses between the number of rural inhabitants per km^2 and density of deforested land for municipalities intercepting the BR-163 corridor. Density of deforested land is calculated at the municipal level by using 1996's Tropical Rain Forest Information Center (TRFIC) forest cover map; population data come from 1996 population tallied by IBGE.

about 84% of the land (Fig. 7). On the other hand, this coefficient is much lower for the Pará and Amazonas municipalities comprised by the analyses, where properties over 200 ha hold only, on average, 34% of the land (Table 1). Thereof, the agrarian concentration determines the regression coefficients *a* and *b* of Eqn (8) according to a lookup table derived from the subregions' agrarian data (Fig. 5b). Agrarian concentration was set to occur in all scenarios, but much less in the governance scenario.

The term *agent_mot* in Eqn (4) represents the agent's motivation to change the landscape and varies for each scenario. This term combines the integrated effect of scenario variables on a transition *j* (*j* = deforestation, land abandonment, or regrowth clearing) caused by a particular agent (*i* = small landholders or farmers and cattle ranchers)

$$agent\_mot_{i,j,t} = (1+cc)^{\left(gov\_level_{scenario,t}\,(int\_ef_{i,j,scenario} - int\_ef_{i,j,bu\sin ess}) + \frac{acc\_factor_t \times int\_ef_{i,j,bu\sin ess}}{max\_acc\_factor}\right)} \quad (9)$$

where *cc* is a calibration coefficient greater than zero and *int_ef* represents the integrated effect of scenario variables that motivate or inhibit the agents behavior, in this case, to clear-cut the forest. As previously described, these qualitative variables are set for each scenario, according to our knowledge and field experience, and are synthesized in the bottom row of Table 3. The *acc_factor* is the same variable used in Eqn (7) and *max_acc_factor* corresponds to the maximum value of *acc_factor* as depicted in Fig. 5.

The integrated effect of the variables for a given scenario (Table 3) acts upon the agent motivation depending on the acceleration effect (*acc_factor*) resulted from the road paving and the level of governance (*gov_level*) present, at a time *t*, in each subregion. In addition to those measures of governance that are assigned to scenario variables at the onset of each model run, as summarized in Table 3, governance is also treated as a dynamic 'stock' within the model, with values from 0 to 1. Each subregion has its initial quantity and governance flows from one subregion to another. This means that governance increases over time as a function of an exogenous context influenced by the national welfare. Yet governance is not equal everywhere in the Amazon, and it does not appear instantaneously; rather it develops over time at a rate that is highly variable from one region to another. As a result, the stimulatory effect of increasing population on the deforestation rate, given by the anthropic pressure (*anthropic_press* in Eqn (4)), is reduced by the level of governance present in each region under a particular scenario.

Similar to the deforestation rate, the dynamic land abandonment (dr_t) and regrowth-clearing (rd_t) rates are modeled by the following equations:

$$
\begin{aligned}
dr_t = {} & dr_{t-1} \times forest\_recovery_t \\
& \times \sum_i \frac{area_{i,t} \times agent\_mot_{i,landabandonment\,t,t}}{total\_area}, \qquad (10)
\end{aligned}
$$

$$
rd_t = rd_{t-1} \times \sum_i \frac{area_{i,t} \times agent\_mot_{i,regrowthclearing\,,t}}{total\_area}. \qquad (11)
$$

As in the deforestation rate equation, the variable *int_ef* in the agent motivation equation is set qualitatively by Table 3 for both land abandonment and regrowth-clearing transitions. Still the land-abandonment rate, which also initiates regrowth, is influenced by the forest regrowth capacity (*forest_recovery*), which declines as a function of the remaining forest (Eqn (12)). Hence, the Amazonian forest regrowth capacity diminishes as a consequence of massive deforestation, capturing the feedbacks posed by deforestation-driven rainfall inhibition (Shukla *et al.*, 1990; Silva Dias, 2002) and fire (Nepstad *et al.*, 2001)

$$
forest\_recovery_t = 1 + \frac{forest_t - initial\_forest}{forest_t + initial\_forest}. \qquad (12)
$$

The spatial simulation model

The alternative scenarios model is coupled to DINAMICA – a landscape dynamics simulator based on cellular automata model (Soares-Filho *et al.*, 2002a, b) – through the exchange of dynamic transition rates and the initial distribution of land-cover classes.

DINAMICA has been used to simulate a variety of spatial phenomena, such as land-use change and urban growth (Soares-Filho *et al.*, 2002a; Almeida *et al.*, 2003). The original version of DINAMICA (Soares-Filho *et al.*, 2002a) was improved to increase performance and new functions were implemented to allow the program to accommodate a larger number of hypotheses regarding landscape dynamics. We developed a linkage between VENSIM and DINAMICA. In this way, a complex external model (Fig. 6) can be designed using VENSIM's icon–graphical interface and passed on to DINAMICA to be run. Also, to adapt DINAMICA to perform simulations at macro-scale over large geographical regions, such as the BR-163 corridor, a new module, named *road constructor*, was added to DINAMICA's cellular automata model.

Roads are the strongest predictors of tropical deforestation (Kaimowitz & Angelsen, 1998; Nepstad *et al.*, 2001). When a road is opened in a remote region, it gives access to the region's resources, reducing the transport costs associated with land-use activities and stimulating deforestation. A road constructor module was developed based on least-cost-path pushbroom algorithms, as described by Eastman (1989) and Douglas (1994), and coupled to DINAMICA's cellular automata model. The aim of the road constructor module is to extend a road network departing from existing roads, taking into consideration: (1) the region's attractiveness for land-use activities (topography, soils); (2) a friction or cost surface, which is used to derive the least cost pathway; (3) road density per area and; (4) average length of new road segments per step. By combining these parameters, the road constructor can be set to replicate various spatial patterns of Amazonian colonization, e.g. the classical 'fishbone' colonization structure, or the 'organic' type, in which the road network follows the watershed boundaries, like the Machadinho project, Rondonia, Brazil (Batistella & Soares-Filho, 1999). Hence, roads are represented by a dynamic layer that is updated after each software iteration.

Spatially explicit simulations were performed for the 410 km × 1080 km part of the BR-163 corridor (Fig. 1). The simulations used the 1996's forest-cover map from TRFIC as the initial landscape map, and the model was set to run for a time span of 30 years, divided into annual time steps.

The influence of proximate variables, such as roads and topography, on deforestation and other land-cover changes has been analyzed previously (Ludeke *et al*., 1990; Mertens & Lambin, 2000; Soares-Filho *et al*., 2001; Alves 2002a, b). In order to incorporate this spatial influence into the simulations, a spatial database was developed. In addition to the initial landscape map, the database comprised cartographic layers of static variables: vegetation, soil, altitude, slope, protected areas, and distance to BR-163, plus the dynamic layers of distance to all roads, including major and secondary roads, and distance to the forest. As deforestation is autocorrelated with previously deforested land (Soares-Filho *et al*., 2001; Alves, 2002b), the model also included this variable. To compute the integrated influence of proximate variables on the modeled transitions, the static and dynamic input layers were used to produce transition probability maps by calculating their weights of evidence with respect to each type of transition (Fig. 2), as described below. Thereafter, the change allocation process took place through DINAMICA's transition functions that select the cells based on their spatial transition probabilities and neighborhood configuration (Soares-Filho *et al*., 2002a, b, 2003).

Weights of evidence is a Bayesian method traditionally used by geologists to point out areas favorable for geologic phenomena, such as seismicity and mineralization (Goodacre *et al*., 1993; Bonham-Carter, 1994). We adapted this method to select the most important variables needed for the land-cover change analysis as well as to quantify their influences to each type of land-use transition: deforestation, land abandonment, and regrowth clearing. The weights of evidence of a spatial variable on a transition $i \Rightarrow j$ are calculated as follows:

$$O\{D/B\} = O\{D\}\frac{P\{B/D\}}{P\{B/D\}}, \tag{13}$$

$$\log\{D/B\} = \log\{D\} + W^{+}, \tag{14}$$

where $O\{D\}$ is the prior odd ratio of event D, $O\{D/B\}$ is the odd ratio of occurring event D, given a spatial pattern B, and W^{+} is its corresponding weight of evidence. The spatial probability of a transition $i \Rightarrow j$, given a set of spatial data, is expressed by the following equation:

$$P(i \Rightarrow j(x,y)/V) = \frac{e^{\sum_k Wkn_{i \Rightarrow j(V)xy}}}{1 + \sum_{ij} e^{\sum_k Wkn_{i \Rightarrow j(V)xy}}}, \tag{15}$$

where V is a vector of k spatial variables, measured at location x,y and represented by its weights W^{+}_{1xy}, W^{+}_{2xy}, …, W^{+}_{nxy}, being n the number of categories of each variable k. In this way, weights of evidence are assigned for categories of each variable represented by its cartographic layer. Note that $O\{D\}$ is assumed to be equal to one, since this is already set by the transition matrix.

Simulations were run simultaneously for each subregion. DINAMICA allows simulations to be run on a subset of data retrieved from a single database. The subregion simulations are linked by the alternative scenario model and spatially integrated by calculating, after each iteration, dynamic variables, such as distance to deforested land and distance to roads, over the raster maps of the entire region.

To avoid a cumbersome calibration process (simulation duration increases exponentially as a function of number of cells), the cell resolution was set initially to 1 km^2 and refined to 250 m after the spatial model achieved a reasonable calibration. This finer resolution resulted in an array of 1640 × 4320 cells for the whole region. For performance comparison, a 30-step (30-year) simulation for the four subregions required 50 min using 1 km^2 resolution, while for the finer resolution, it takes about 20 h on a standard 1.7 MHz processor.

Model calibration

The alternative scenario model was calibrated to reproduce in the worst-case scenario (business-as-usual with high population growth) the past trends observed where a major road was paved, using a similar approach to Nepstad *et al*. (2000, 2001) and Laurance *et al*. (2001). The advanced frontier of Northern Mato Grosso was used as a baseline for the pristine region of the South of Pará, the region most likely to suffer the largest impact due to the paving of Cuiabá–Santarém road. If trends in deforestation and population growth of South of Pará are similar to historical trends in northern Mato Grosso (Tables 1 and 2), then a 20–24-fold increase in its 1996's deforested land and a 9–10-fold jump in its 1996's population would be expected after 30 years. These calibration values were implemented by changing the acceleration factor (*acc_factor*) and the calibration coefficient (*cc*), in Eqns (7) and (9), together with the lookup table of population growth rate for South of Pará. In this manner, the model also projects dynamic population and urbanization growth rates assuming that there is a convergence towards the regional average of the Amazon region. Hence, growth rates that are far above or below the regional mean growth rate tend to decrease or increase over time, respectively.

As the model was only calibrated for the business-as-usual scenario with high population growth, the other three scenarios represent some degree of deviation from this scenario. In this way, the governance effect on diminishing the rates will develop according to its initial levels (0.2, 0.01, 0.1, 0.15, respectively, for Northern Mato Grosso, South of Pará, Transamazonica and Santarém regions) and regional influx rate, which was set constant and equal to 0.03 per year – approximately three times the GNP per capita annual growth rate, as the model assumes that governance must rise faster than the economic development.

The spatial model was calibrated using a fraction of the study region, where detailed studies have been carried out (see Fig. 1). In the Northern Mato Grosso study areas, weights of evidence were empirically calculated by cross-tabulating multitemporal maps of land use and land cover (from 1997 to 1999) with cartographic layers of the variables: vegetation, soil, altitude, slope, distance to main road, distance to secondary roads, distance to the forest, and distance to previously deforested land. The 'vegetation' variable was excluded due to its spatial correlation with soil.

Figures 8 and 9 show the spatial relationships of analyzed variables with respect to deforestation and land abandonment. Some spatial relationships, such as

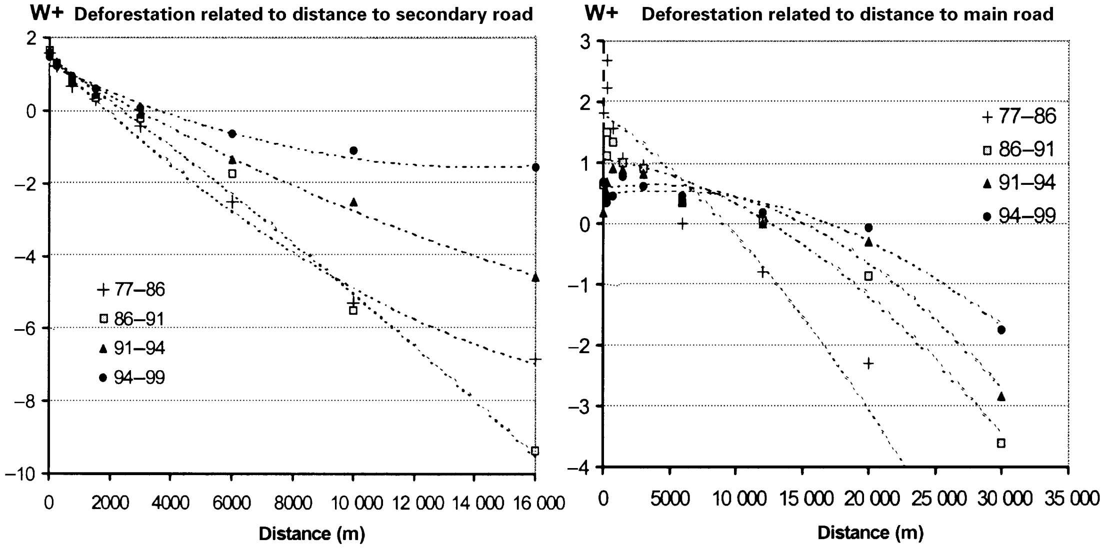

Fig. 8 Effects of spatial variables on deforestation, as shown by weights of evidence. The trend lines represent adjusted second order polynomials.

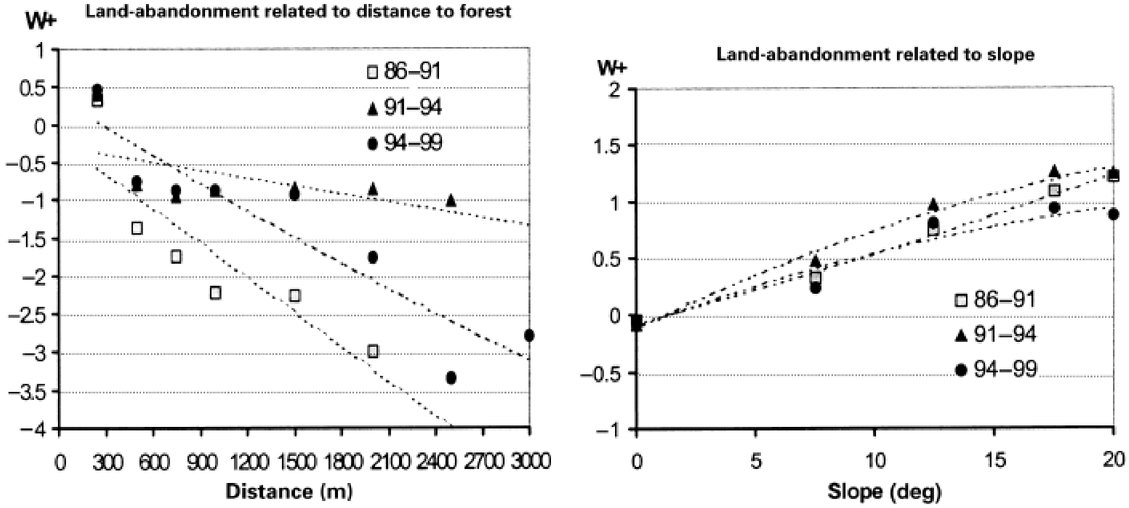

Fig. 9 Effects of spatial variables on land abandonment, as shown by weights of evidence. The trend lines represent adjusted second-order polynomials.

percentage of deforestation in relation to distance to main road, vary over time and can be used as dynamic coefficients to characterize distinct phases of the deforestation process represented in the model. The weights of evidence also varied as a function of the alternative scenarios. Protected areas were assigned with a strong negative weight for the deforestation transition in the governance scenario, whereas the protected areas did not slow much deforestation in the business-as-usual scenario.

The parameters of the road constructor module were fine-tuned to obtain a final road network that slightly exceeds the deforestation front and presents a density and structure similar to the fishbone road network commonly found in the Brazilian Amazon.

For calibration of DINAMICA's transition functions (Soares-Filho *et al*., 2002a) and macro-scale validation, simulations were run for the Northern Mato Grosso case study area, encompassing a time span from 1986 to 1999. This area comprises 19 000 km^2 and is represented by a raster map of 566 × 704 cells at 250 m resolution. By comparing the simulation output maps with the reference landscape, the model could be fine-tuned to replicate the evolving spatial pattern of this region's landscape dynamics. The calibrated spatial model was then extended to the other corridor subregions.

Results

The model was run for business-as-usual and governance scenarios with high and moderate population growth. Although other scenarios could emerge by modifying the GNP per capita growth rate, this variable was set constant and assumed to be the annual average of the last decade (0.01 per year). The projected deforestation rates and forest declines for the four scenarios and subregions are given in Figs 10 and 11.

Northern Mato Grosso is closest to the agricultural zone of central Brazil, and has experienced higher rates of deforestation than the other subregions. It seems likely that these rates will tend to decline, since this area already presents some level of governance and its rural population is stabilized as indicated by its high migratory flux from rural to urban areas and to elsewhere in Amazonia (Table 1). Thus, the historical deforestation rate is higher than those estimated from

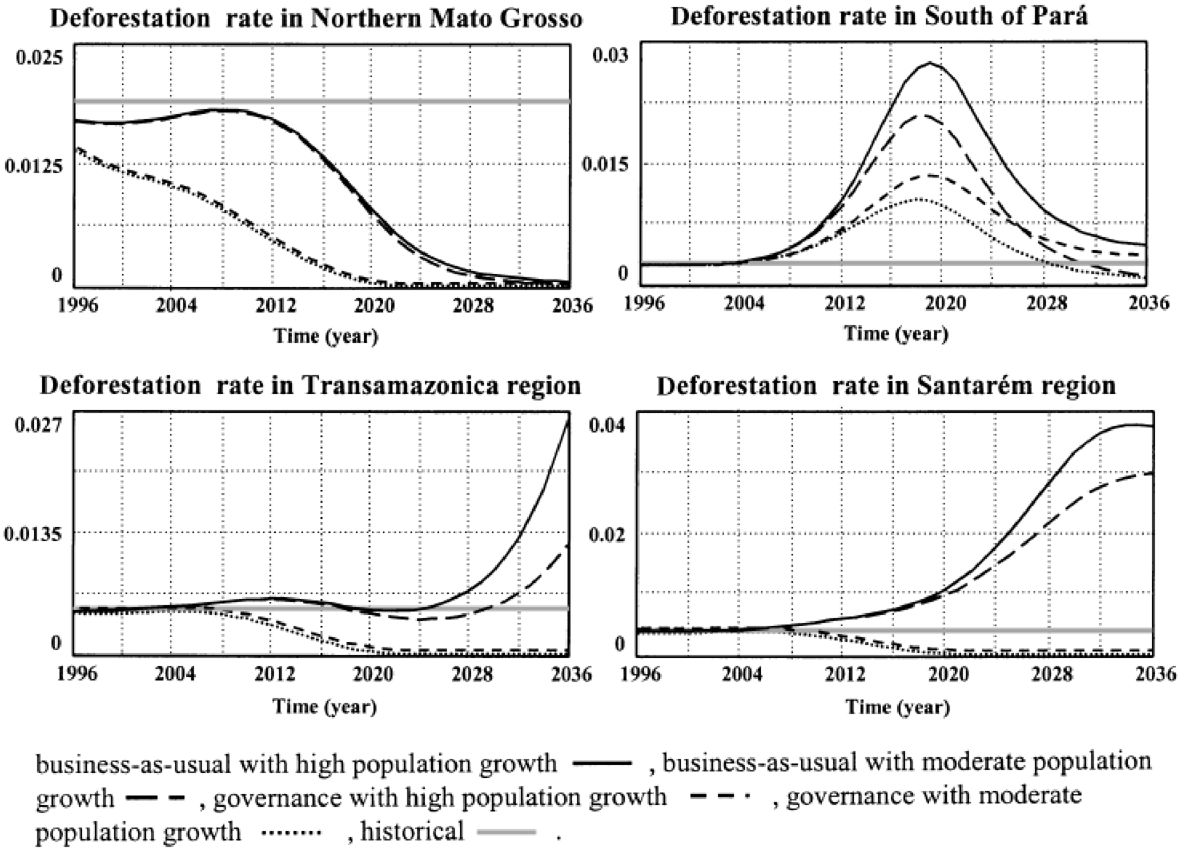

Fig. 10 Dynamic rates output by the alternative scenarios compared with the historical baseline.

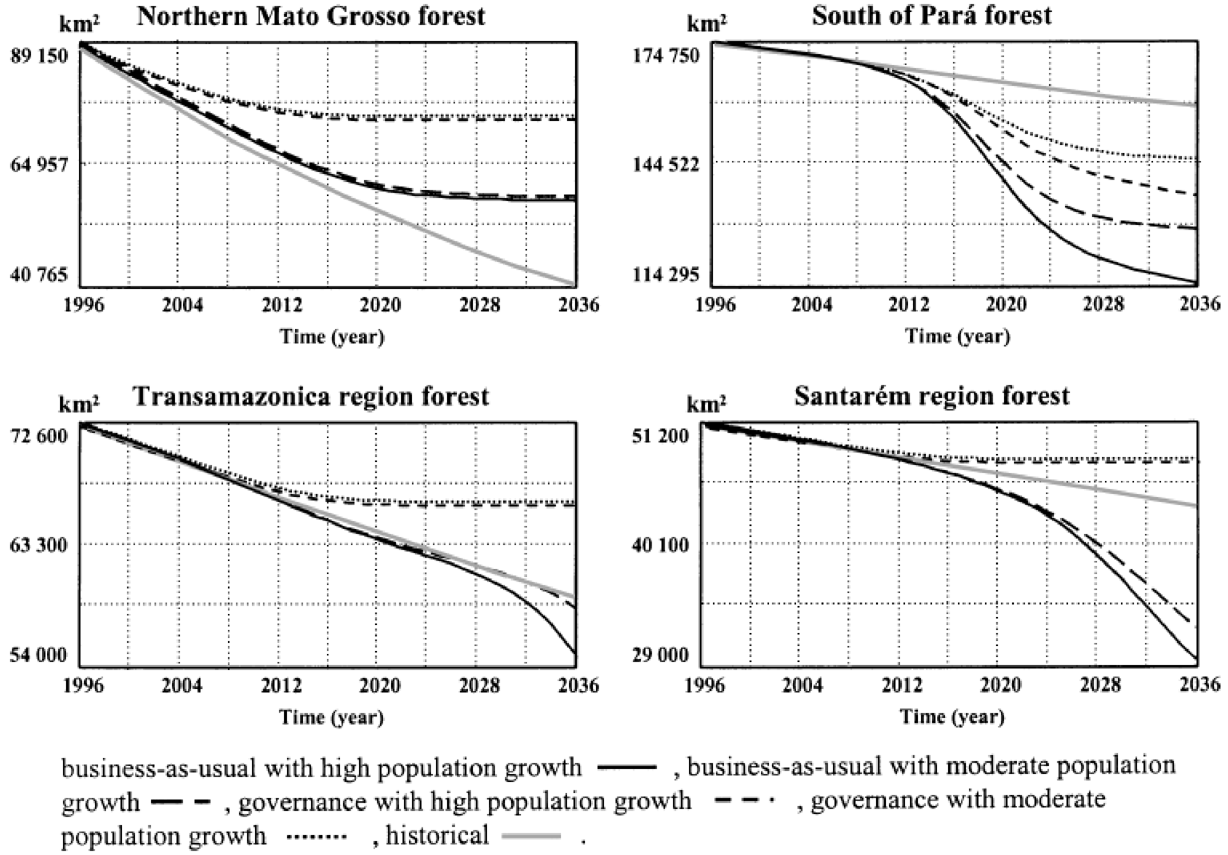

Fig. 11 Forest decline in the four scenarios and subregions.

current anthropic pressure, and a downward trend in deforestation rates is predicted. For this subregion, the governance scenario enhances this decline in the deforestation rate.

South of Pará emerges as the subregion most affected by highway paving and consequently population growth, since its historical deforestation rate is the lowest among the subregions. All scenarios produce increasing deforestation rates. However, the upward effect of population growth on the deforestation rate can be strongly reduced through governance.

In turn, the various scenarios produce similar effects on the deforestation rates of Transamazonica and Santarém regions, the latter being more affected by the population growth due to its higher initial population. In both cases, the rise of the deforestation rate is delayed until population growth reaches a threshold; high level of governance inverts the upward effect of population growth.

The most conspicuous forest decline projected by the model is in South of Pará (Fig. 11), although the Santarém region shows the highest relative decline because of its strategic position as a burgeoning urban center. Northern Mato Grosso is the only subregion where the worst-case scenario – the business-as-usual scenario with high population growth – shows deforestation rates lower than the historical trend, as explained above (Fig. 10).

The model estimates that after 30 years the total area of forest in the region will decline from 386 000 to 256 000 km^2 (34% reduction) for the business-as-usual scenario with high population growth, and to 325 000 and 334 000 km^2 (16% and 13% reductions) for the governance scenarios with high and moderate population growth, respectively. Therefore, governance could potentially entail up to 60% reduction in the expected deforestation due to the paving of Cuiabá–Santarém road, if all the measures envisaged for this scenario are thoroughly realized within the region.

The extreme case scenarios – the business-as-usual scenario with high population growth and the governance scenario with moderate population growth – were chosen to run the spatial simulations (Fig. 12). Although these maps are only a set of possible results, one can notice the thorough preservation of the protected areas and the more intensive use of the deforested land in the governance scenario, whereas in the business-as-usual scenario, the forest reserves close

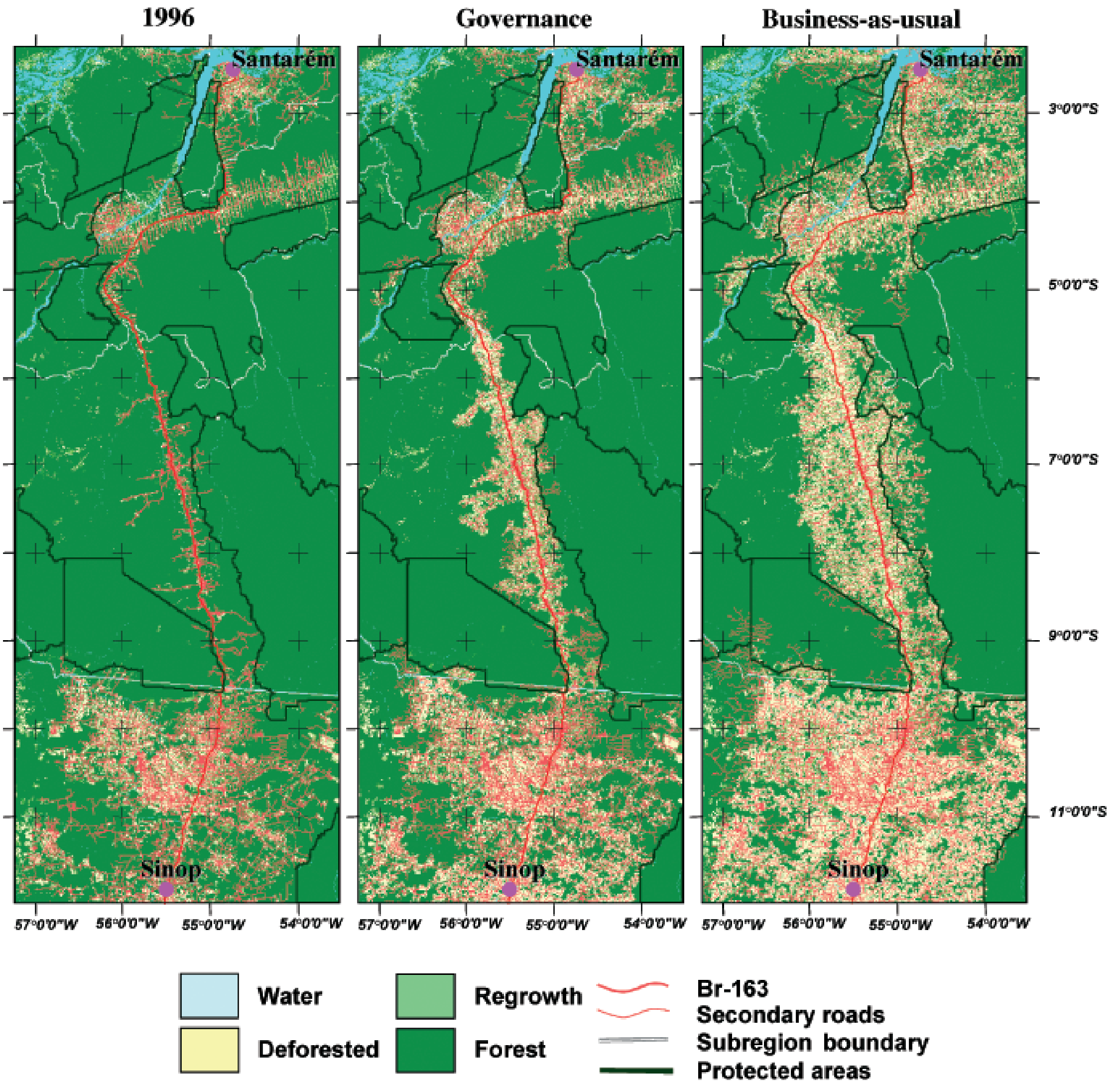

Fig. 12 Map outputs from the extreme case scenarios. Run for 30 years: business-as-usual with high population growth and governance with moderate population growth.

to the Cuiabá–Santarém road are partially despoiled and the landscape is much more fragmented, resulting in numerous forest remnants surrounded by a myriad of regrowth patches in diverse stages of succession. In this last case, the road network has expanded more, producing extensive edge habitats that may lead to further impoverishment of the remaining forest.

Discussion

Deforestation in the Brazilian Amazonia can be partially explained in terms of the paucity of social and economic opportunities in other regions of Brazil, which creates an abundance of economic actors available to occupy and exploit the new lands opened up through Amazon highways. This phenomenon accounts for the high influx of people towards the South of Pará, most of them coming from the neighboring region of Northern Mato Grosso, where towns, like Guarantã do Norte, have become the base from which entrepreneurs access the coveted lands of the South of Pará. The paving of Cuiabá–Santarém Road will certainly facilitate this process, which is, today, still hampered by the Cachimbo ridge, a 130 km wide area of unproductive sandy soils, lying right along the Pará and Mato Grosso border.

The flow of agents among the subregions of the BR-163 corridor is mimicked by the alternative scenarios model, making it effective in reproducing our current knowledge of this Amazonian region's frontier dynamics. Although the alternative scenarios model is semi-quantitative, with governance effects highly sensitive to different expert views, it is designed to incorporate measured quantitative linkages between deforestation, population and GNP per capita. The model does not use population growth alone as the driving force of deforestation in Amazonia, but integrates the effects of several variables, including agrarian trend, urbanization level, and agents' responses to the policy–economic scenarios. Furthermore, our approach also introduces a way to incorporate local people's perception and demands.

In turn, the spatial model, DINAMICA, provides a flexible tool to explore the spatial patterns that might evolve under the various scenarios, thereby allowing us to evaluate their potential environmental outcomes such as habitat loss and fragmentation. As a result, the model could be applied to designing protected areas considering that it could indicate areas more likely to be deforested and deforested land that could evolve to secondary forests.

The model allows us to integrate our knowledge of Amazon land-use dynamics, and consequently test a large number of hypotheses concerning its landscape evolution. Thus, its overall structure can be used as a guide to develop new simulation models of key Amazon regions, as well as to build a Panamazonian landscape dynamics model. In a subsequent version of the model, we will incorporate the dynamics of logging and forest fire and develop quantitative measurements of governance.

Concluding remarks

Forest conversion to cattle pasture and agriculture will be stimulated by the paving of the BR-163 highway, but the magnitude of this effect is responsive to interventions by government and civil society that have begun to appear in recent years (Laurance, 1998; Nepstad *et al*., 2002). Nevertheless, historically, effective conservation measures come too late to protect large tracts of undisturbed forest, typically leaving the region's communities with a depleted natural resource base. Governance can be viewed as a force promoting appropriate land uses and inhibiting inappropriate economic activities against the frontier system's exploitative 'entropy'; but, analog to the 'Holling Cycle' (Holling, 1987), the force of governance grows more slowly than the force of exploitation. Hence, the model may be useful in identifying the rate and timing at which governance should increase before the current deforestation process thoroughly impoverishes this and other regions of the Amazon. Moreover, the alternative scenarios model may be used as an instrument to help us measure and promote the crucial role of governance in the conservation of this vital ecosystem.

Acknowledgements

This project was only made possible through the close collaboration of the 'Scenarios Project' participants. It is a work done by many hands; therefore we would like to acknowledge the crucial contribution from all our colleagues, who directly or indirectly collaborated to this work, especially Peter Schlesinger, Paul Lefebvre, Socorro Pena, and Tim Killeen.

We also thank CABS/CI (Center for Applied Biodiversity Science at Conservation International), the US Agency for International Research, and LBA-ECO – the Large-Scale Atmosphere–Biosphere Experiment (through funding from National Aeronautics and Space Administration) for funding.

First author also receives support from FAPEMIG (Fundação de Apoio à Pesquisa de Minas Gerais – CRA2463/98) and CAPES (Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – BEX0438/02-2).

References

Alencar A, Nepstad D, Silva E *et al*. (1997) O *uso do fogo na Amazônia: estudos de caso ao longo do arco de desmatamento*, World Bank Report, Brasilia.

Almeida C, Batty M, Monteiro AM *et al*. (2003) Stochastic cellular automata modelling of urban land use dynamics: empirical development and estimation. *Computers, Environment and Urban Systems*, **27**, 481–509.

Alston LJ, Libecap GD, Mueller B (2000) Land reform policies, the sources of violent conflict, and implications for deforestation in the Brazilian Amazon. *Journal of Environmental Economics and Management*, **39**, 162–188.

Alves D (2002a) An analysis of geographical patterns of deforestation in Brazilian Amazônia the 1991–1996 period. In: *Patterns and Processes of Land use and Forest Change in the Amazon* (eds Wood C, Porro R), University of Florida, Gainesville.

Alves DS Space–time dynamics of deforestation in Brazilian Amazônia. *International Journal of Remote Sensing*, **24**, 2903–2908.

Batistella M, Soares-Filho BS (1999) Ensaio Comparativo da Fragmentação da Paisagem em função de modelos arquitetônicos de assentamento rural em Rondônia. In: *GIS-Brasil, 1999* (CD-ROM). FatorGis, Salvador, Br.

Bonham-Carter G (1994) *Geographic Information Systems for Geoscientists: Modelling with GIS*. Pergamon, New York.

Carvalho G, Barros AC, Moutinho P *et al*. (2001) Sensitive development could protect Amazonia instead of destroying it. *Nature*, **409**, 131.

Chomitz KM, Gray DA (1996) Roads, lands, markets, and deforestation, a spatial model of land use in Belize. *World Bank Economic Review*, **10**, 487–512.

Douglas DH (1994) Least-cost path in GIS using an accumulated cost surface and slopelines. *Cartographica*, **31**, 37–51.

Eastman JR (1989) Pushbroom algorithms for calculating distances in raster grids. In: *AUTOCARTO 9* Baltimore, MO, USA. pp. 288–297.

Fearnside PM (1985) Agriculture in Amazonia. In: *Key Environments of Amazonia* (eds Prance GT, Lovejoy TE), pp. 393–418. Pergamon Press, Oxford.

Fearnside PM (1993) Deforestation in Brazilian Amazonia: the effect of population and land tenure. *Ambio*, **22**, 537–545.

Fearnside PM (1996) Amazonian deforestation and global warning: carbon stocks in vegetation replacing Brazil's Amazon forest. *Forest Ecology and Management*, **80**, 21–34.

Fearnside PM (2001) Land-tenure issues as factors in environmental destruction in Brazilian Amazonia: the case of Southern Pará. *World Development*, **29**, 1361–1372.

Geist HJ, Lambin EF (2002) *A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence*. LUCC Report Series, 4 http://www.geo.ucl.ac.be/LUCC/lucc.html.

Goodacre CM, Bonham-Carter GF, Agterberg FP *et al*. (1993) A statistical analysis of spatial association of seismicity with drainage patterns and magnetic anomalies in western Quebec. *Tectonophysics*, **217**, 205–305.

Hecht S, Norgaard R, Possio G (1988) The economics of cattle ranching in eastern Amazonia. *Interciencia*, **13**, 233–240.

Holling CS (1987) Simplifying the complex: the paradigms of ecological functions and structure. *European Journal of Operational Research*, **30**, 139–146.

Houghton RA (1999) The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus*, **51B**, 298–313.

Instituto Brasileiro de Geografia e Estatística (IBGE) (1991) *Censo Demográfico de 1991 (CD-ROM)*. IBGE, Rio de Janeiro, Br.

Instituto Brasileiro de Geografia e Estatística (IBGE) (1996a) *Censo Agropecuário de 1995/1996 (CD-ROM)*. IBGE, Rio de Janeiro, Br.

Instituto Brasileiro de Geografia e Estatística (IBGE) (1996b) *Contagem de 1996 (CD-ROM)*. IBGE, Rio de Janeiro, Br.

Instituto Brasileiro de Geografia e Estatística (IBGE) (2000) *Censo Demográfico de 2000 (CD-ROM)*. IBGE, Rio de Janeiro, Br.

Instituto Nacional de Pesquisas Espaciais (INPE) (2002) Monitoring of Brazilian Amazonian Forest by Satellite 2000⟨http://www.grid.inpe.br/papers.html⟩(June 2002)

Kaimowitz D, Angelsen A (1998) *Economic Models of Tropical Deforestation. A Review.* Center for International Forestry Research, Bogor.

Laurance WF (1998) A crisis in the making responses of Amazonian forests to land use and climate change. *Tree*, **13**, 411–415.

Laurance WF, Cochrane MA, Bergen S *et al*. (2001) The future of The Brazilian Amazon. *Science*, **291**, 438–439.

Ludeke A, Maggio RC, Reid LM (1990) An analysis of anthropogenic deforestation using logistic regression and GIS. *Journal of Environmental Management*, **31**, 247–259.

Mahar DJ (1988) *Deforestation in Brazil's Amazon Region: Magnitude, Rate and Causes*. The World Bank, New York.

Mattos M, Uhl C (1994) Economic and ecological perspectives on ranching in the eastern Amazon in the 1990s. *World Development*, **22**, 145–158.

Mertens B, Lambin EF (1997) Spatial modelling of deforestation in Southern Cameroon: spatial disaggregation of diverse deforestation processes. *Applied Geography*, **17**, 143–168.

Mertens B, Lambin EF (2000) Land-cover change trajectories in Southern Cameroon. *Annals of the Association of American Geographers*, **205**, 467–494.

Messina JP, Wash SJ (2000) The application of a cellular automaton model for predicting deforestation: patterns and processes of LULCC in the Ecuadorian, Amazon. In: *Fourth International Conference on Integrating GIS and Environmental Modeling Problems, Prospects and Research Needs*. GIS/EM4, Banff, CA.

Ministério do Desenvolvimento, da Indústria e Comércio Exterior (MDIC) (2002) Anuário Estatístico ⟨http://www.mdic.gov.br/indicadores/Outras_Estatisticas/anuarioEstatistico.html⟩ (November 2002).

Nelson GC, Harris V, Stone SW (1999) *Spatial Econometric Analysis and Project Evaluation: Modeling Land Use Change in the Darién*. InterAmerican Development Bank, Washington, DC.

Nepstad D, Capobianco JP, Barros AC *et al*. (2000) Avança Brasil, the environmental costs for Amazônia. <http://www.ipam.org.br/avanca/participen.htm> (November 2002).

Nepstad D, Carvalho G, Barros AC *et al*. (2001) Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecology and Management*, **5524**, 1–13.

Nepstad D, McGrath D, Alencar A *et al.* (2002) Frontier governance in Amazonia. *Science*, **295**, 629–631.

Nepstad D, Moreira A, Alencar A (1999a) *Flames in the Rainforest: Origins, Impacts and Alternatives to Amazon Fire. Pilot Program for the Conservation of the Rainforests of Brazil*. World Bank, Washington.

Nepstad D, Verissimo A, Alencar A *et al*. (1999b) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature*, **398**, 505–508.

Pfaff ASP (1999) What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management*, **37**, 26–43.

Putnam RD, Leonardi R, Nanetti RY (1992) *Making Democracy Work Civic Traditions in Modern Italy.* Princeton University Press, Princeton, NJ.

Reis E, Guzmán R (1994) An econometric model of Amazon deforestation. In: *The Causes of Tropical Deforestation, The Economic and Statistical Analysis of Factors Giving Rise to the Loss of Tropical Forests* (eds Brown K, Pearce D), pp. 172–191. University College London Press, London.

Schmink M, Wood CH (1992) *Contested Frontiers in Amazonia*. Columbia University Press, New York.

Shukla J, Nobre C, Sellers PJ (1990) Amazon deforestation and climate change. *Science*, **247**, 1322–1325.

SilvaDias MAF, Rutledge S, Kabat P *et al*. (2002) Cloud and rain processes in a biosphere-atmosphere interaction context in the Amazon Region. *Journal of Geophysical Research*, **107**, 39.1–39.18.

Skole DL, Chomentowski WH, Salas WA *et al*. (1994) Physical and human dimensions of deforestation in Amazonia. *BioScience*, **44**, 314–322.

Soares-Filho BS (2001) Fragmentação da Paisagem Florestal em Função da Estrutura e Dinâmica Fundiária no Norte do Mato Grosso. In: *X Simpósio Brasileiro de Sensoriamento Remoto* (pp. 21–26. Instituto Nacional de Pesquisas Espaciais, Foz do Iguaçu, Br.

Soares-Filho BS, Assunção RM, Pantuzzo A (2001) Modeling the spatial transition probabilities of landscape dynamics in an Amazonian colonization frontier. *BioScience*, **51**, 1039–1046.

Soares-Filho BS, Cerqueira G, Araujo W *et al*. (2002b) *DINAMICA project*. <http://www.csr.ufmg.br/dinamica> (November 2002).

Soares-Filho BS, Corradi L, Cerqueira G *et al*. (2003) Simulating the spatial patterns of change through the use of the DINAMICA model. In: *XI Simpósio Brasileiro de Sensoriamento Remoto* (pp. 721–728. Instituto Nacional de Pesquisas Espaciais, Belo Horizonte, Br.

Soares-Filho BS, Pennachin C, Cerqueira G (2002a) DINAMICA – a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. *Ecological Modelling*, **154**, 217–235.

Stern D, Common M, Barbier E (1996) Economic growth and environmental degradation: the environmental kuznets curve and sustainable development. *World development*, **24**, 1151–1160.

Turner BL II, Meyer WB, Skole D (1994) Global land-use/landcover change: towards an integrated study. *Ambio*, **23**, 91–95.

Ventana (2002) Vensim software – linking systems thinking to powerful dynamic models. ⟨http://www.vensim.com/software.html⟩ (November 2002).

Veríssimo A, Barreto P, Mattos MM *et al*. (1992) Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: the case of Paragominas. *Forest Ecology and Management*, **55**, 169–199.