FAPESP RESEARCH PROGRAMME ON GLOBAL CLIMATE CHANGE

Land Use Change in Amazonia: Institutional Analysis and Modeling at multiple temporal and spatial scales

Final Report – April, 2014

Project Period Covered: March 2010 to February 2014

1 INTRODUCTION

This project aims to understand and model the causes that contribute to deforestation in Amazonia. Biomass burning associated with deforestation is responsible for most of Brazil's greenhouse gas emissions. We argue that land changes in Amazonia are brought about by social and institutional arrangements. Understanding these social and institutional forces is critical for evaluating and proposing deforestation control policies that also reduce greenhouse gas emissions. Thus we propose to explore the following core scientific question: *What are the relations between changes in land use and the evolution of institutional arrangements in Amazonia?* These arrangements include agreements or conventions set up between interest groups, social movements, organizations, and state agencies. Negotiated at different scales (from local to international), they influence the legal rules of use of natural resources and territorial occupation. They also restrict law enforcement. Since the 1960s, Amazonia has witnessed the buildup of institutional arrangements often associated to competing ways of using natural resources and to different economic goals. In our view, institutional arrangements in Amazonia provide the key to the causes of land change in the region in the last 40 years.

Many institutional arrangements that define land use in Amazonia reflect the interests of private groups. These groups use social, political, ideological, and legal means to control the region. Asserting control over the land, ruling groups use their power to keep social inequality. For example, credits granted by state agencies are often used to support political alliances related to allied with private interests. Such a view explains how Amazonian elites seize the land and expropriate the poor. From the 1970s to the 1990s, efforts to control the area led to unexpected results, allowing deceit in the rules of land use. However, recent institutional evolution in Amazonia is increasingly motivated by rules that promote environmental conservation. Since the 1990s, there are new legal limits on the use of natural resources, which include community land rights. New protected areas have been created. The Federal Government has increased law enforcement. New laws also mandate formal representation of local populations in city councils and regional development forums. This motivates an important question: *how do competing institutional arrangements for managing resources help to promote or undermine good solutions to the problems of land use in Amazonia?*

The project is organized on four interrelated lines of research, combining methods from different academic areas, including social analysis, remote sensing, landscape ecology, and mathematical modeling:

- **Axis 1**: *Identification and analysis of institutional arrangements* that influence land change, using social sciences and statistical methods.
- **Axis 2**: *Measurement and mapping of land change*, using novel remote sensing and image processing methods.
- **Axis 3**: *Detection and analysis of land occupation patterns and trajectories*. These patterns emerge from land changes related to the institutional arrangements mentioned above.
- **Axis 4**: *Construction of computational models and scenarios* that capture how social interactions and institutional arrangements act on land change.

This report is organized as follows. Section 2 presents the main findings of the project. Section 4 presents the research highlights. Section 5 summarizes the project and discusses future plans. The complete list of scientific results is presented in the Annex.

2 Main findings of the project

(N.B. All of the papers cited have been produced as part of the project, unless specifically stated).

This project has brought together researchers from different backgrounds towards a common goal: understanding how land change happens in Amazonia. Our approach to this problem is to try to indentify and recognize the complexity of the decisions taken at an individual and local levels. In this project, we have tried to understand how these local decisions are reflected in the overall patterns and processes of change.

In the last two decades, there has been major scientific progress in the methods for large-scale monitoring and mapping of land cover change in Amazonia. Methodologies such as those used by INPE in its projects PRODES, DETER and TERRACLASS have enabled the Brazilian government to achieve a substantial reduction on deforestation. This emphasis on "top-down" approaches to study change in Amazonia is also reflected in most research works that try to explain the process of land change in Amazonia. In most case, these studies take use of an econometric-based approach, where data on land change extracted from remote sensing images is correlated with data on land use selected from the Population and Agricultural Census. We value the usefullness of this approach, but we also recognize its limits. Thus, a large part of our effort in this project has been dedicated to a dialogue with this established research tradition.

There is a considerable degree of intraregional variations in Amazonia due to the local decision-making arrangements, as we had already recognized in previous work leading up to the project[1]. Thus, a major part of our efforts in the project have been devoted to understand how these local actions and arrangements are reflected in the overall patterns of deforestation. In this way, we have been able to combine the econometric

[1] Ana Aguiar, Gilberto Câmara, and Maria Isabel Escada. 2007. "Spatial statistical analysis of land-use determinants in the Brazilian Amazon: exploring intra-regional heterogeneity." *Ecological Modelling* no. 209 (1-2):169–188.

“top-down” approach with a “bottom-up” that recognizes the importance of the local arrangements.

In this light, we describe the main findings of the project below.

We showed that improvements on statistical analysis, such as better methods for putting census data on cell spaces[2] and spatio-temporal inferences, can lead to improvements on our understanding of the relations between land use and land cover[3]. Nevertheless, we also found out that there are inherent limits to the predictive power of the “top-down” econometric approach. The main problem is that projecting the correlations found in econometric and statistical models to the future, assumes that these relations will not change substantially. In one of our published papers[3], we showed that the correlation between variables associated to land use and deforestation changed between 1997 and 2007, in some cases quite substantially.

We also carried out *ex-post* evaluations of previous work by other authors that tried to predict future scenarios of land change based on econometric methods and found they have limited explanatory power[4,5]. We found out that the previous land use modeling studies were not able to plausibly capture the general trajectory of land cover change observed in the Amazon during the last decade. We found out that regional policies generated a greater demand for the regulation of the productive sectors, which had a decisive effect for the immediate reduction of deforestation. From our studies, we concluded that we need to represent Amazonian land

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[2] Giovana Espindola, Ana Aguiar, Pedro Andrade, 2012. “Combining Satellite Remote Sensing and Census Data for Regional Scale Analysis of Land Use Change in the Brazilian Amazon”. *Revista Brasileira de Cartografia*, 64(5).

[3] Giovana Espindola, Ana Paula Aguiar, Edzer Pebesma, Gilberto Câmara, Leila Fonseca, 2012. “Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data”. *Applied Geography*, 32(2):240-252.

[4] Eloi Dalla-Nora, Ana Aguiar, David Lapola, Geert Woltjer, 2014. “Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade?”, *Land Use Policy*, 39, pp. 403–411.

[5] Luiz Diniz, Merret Buurman, Pedro Andrade, Gilberto Camara, and Edzer Pebesma. "Measuring Allocation Errors in Land Change Models in Amazonia." Brazilian Symposium on Geoinformatics, 2013.

use processes as complex systems. The next generation of land use models needs to capture both “top-down” driving forces such as government policies and agrarian structure, but also represent “bottom-up” decision-making by local actors.

As a contribution to the understanding of “bottom-up” processes, the project researchers did a major effort to analyse and classify land change patterns in Amazonia. This work enabled us to identify significant differences in the occupation patterns, comparing different regions in Amazonia[6] [7].

Our research is supported by a theoretical concept of extensive urban in Amazônia proposed by Monte-Mór[8], in which the urban is seen as a phenomenon that spans the territory, in a continuous, where a large set of socio-spatial forms, beyond the cities and towns, is organized. Cities, riparian communities, rural villages, settlement projects, protected areas, indigenous lands and farms, are examples of types of land occupation that are present in the Amazonian municipalities[9].

In Amazonia, we have the indigenous peoples and the migrants that moved to the region in the late 19th and early 20th Century. However, the most important land changes in Amazonia results from the migrations that took place after the 1970s. Often, these migrants came for urban or periurban regions. Colonization was organized and sanctioned by the government and based on creating a network of new towns or increasing urban population of existing cities. Based on the hypothesis that the key to understanding the land changes in Amazonia lies in the urban networks, considering the diferent manners in which urban manifests on the territory,

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[6] Taise Pinheiro, Isabel Escada*. “Detection of forest degradation in Amazonia using celludar databases. XVI Brazilian Symposium on Remote Sensing (SBSR), Foz de Iguaçu, 2013.

[7] André Gavlak, Isabel Escada*, Miguel Monteiro, “Dinamics of land use and land cover change in the Sustainable Forest District along BR-163 road. XV Brazilian Symposium on Remote Sensing, Curitiba, PA, 2011.

[8] Roberto Monte-Mór. Urbanização Extensiva e Lógicas de Povoamento: Um Olhar Ambiental. In: SANTOS, M.; SOUZA, M. A. A. de.; SILVEIRA, M. L. (Ed.). Território, Globalização e Fragmentação. São Paulo: HUCITEC-ANPUR, 1994, p. 169-181.

[9] Ana Cláudia Duarte Cardoso; José Júlio Ferreira Lima. Tipologias e padrões de ocupação urbana na Amazônia Oriental: para que e para quem? In: Cardoso, A. C. D. (Ed.). O Rural e o Urbano na Amazônia. Diferentes olhares e perspectivas. Belém-PA: EDUFPA, 2006, p.55-98.

and in the institutional and market connections, we carried out research on urban settlements in the region[10 11]. We found out that the institutional arrangements that shape the individual decisions are based on urban settlements.

As part of our research, we found out that the current information on land cover change in Amazonia provided by INPE (PRODES, DETER and DEGRAD) although essential for monitoring deforestation, is insufficient to enable us to model the complexity of the processes of land change in Amazonia. For this reason, we invested in the techniques to improve extraction of land change information from remote sensing images. These techniques include improvements on methods for analising multisensor and multitemporal imagery.

Our results in the project have studied the combination of optical and radar data to map urban areas in Amazonia[12]. Our results point out that the complex urban–rural landscape patterns in Amazonia cannot be effectively well mapped by LANDSAT TM multispectral images with 30 m spatial resolution. These urban-rural landscapes require image with 10 m spatial resolution or better.

We also investigated the use of multitemporal data (especially long term MODIS and AVHRR time-series) to detect land use transitions in the agricultural areas in Amazonia[1314]. Our results indicate that time-series of

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[10] Silvana Amaral*, André Gavlak, Isabel Escada*, and Miguel Monteiro, "Using remote sensing and census tract data to improve representation of population spatial distribution: case studies in the Brazilian Amazon", *Population and Environment*, 34:142-170, 2012.

[11] Ana Paula Dal'Asta, Newton Brigatti, Silvana Amaral*, Isabel Escada* and Antonio Miguel Monteiro. "Identifying Spatial Units of Human Occupation in the Brazilian Amazon Using Landsat and CBERS Multi-Resolution Imagery". *Remote Sensing*, 4: 68-87, 2012.

[12] Dengsheng Lu, Guiying Li, Emilio Moran, Mateus Batistella, and Corina Freitas*, "Mapping impervious surfaces with the integrated use of Landsat Thematic Mapper and radar data: A case study in an urban–rural landscape in the Brazilian Amazon." ISPRS Journal of Photogrammetry and Remote Sensing 66(6): 798-808, 2011.

[13] Damien Arvor, Margareth Meirelles, Vincent Dubreil, Agnès Bégué, and Yosio Shimabukuro*, "Analyzing the agricultural transition in Mato Grosso, Brazil, using satellite-derived indices". *Applied Geography*, 32: 702-713, 2012.

MODIS, SPOT-VGT and PROBA satellite data can be useful to detect changes in crop production in regions such as Mato Grosso, where the crop areas are large enough to be detected by satellites with low spatial resolution and high temporal resolution. We also looked into the role of forest fires in making the Amazon forest more vunerable to deforestation[15] [16]. We found out that forest fires are playing an important role as precursors of later deforestation actions.

The project also had a significant component on the development of software for environmental modeling, which was necessary to support the research of scenarios of future deforestation and on analysis and description of the current landscapes in Amazonia. The main result of the project in this area was the development of mature versions of TerraME, an innovative toolkit for modeling nature-society interactions[17]. The TerraME software supported innovative studies by the project researchers, such as agent-based modeling of deforestation in São Felix do Xingu[18] and the development of INPE-EM, a detailed model for measuring emissions from deforestation[19].

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[14] Atzberger, C., A. R. Formaggio, Yosio Shimabukuro*, T. Udelhoven, M. Mattiuzzi, G. A. Sanchez, and E. Arai. "Obtaining crop-specific time profiles of NDVI: the use of unmixing approaches for serving the continuity between SPOT-VGT and PROBA-V time series." International Journal of Remote Sensing 35, no. 7 (2014): 2615-2638.

[15] Luiz Aragão, and Yosio Shimabukuro*, "The incidence of fire in Amazonian forests with implications for REDD." *Science* 328(5983) 1275-1278, 2010.

[16] Fletcher, I. N., L. E. O. C. Aragão, A. Lima, Y. Shimabukuro*, and P. Friedlingstein. "Fractal properties of forest fires in Amazonia as a basis for modelling pan-tropical burned area." Biogeosciences Discussions 10, no. 8, 2013.

[17] Tiago Carneiro, Pedro Andrade*, Gilberto Câmara*, Miguel Monteiro, Rodrigo Reis Pereira, "An extensible toolbox for modelling nature-society interactions". *Enviromental Modelling and Software*, 46: 104-117, 2013.

[18] Sergio Costa, "Regional Scale Agent-Based Modelling of Land Change: Evolving Institutional Arrangements in Frontier Areas". PhD dissertation in Computer Science, INPE, 2012. Advisors: Gilberto Câmara* and Ana Paula Aguiar*.

[19] Ana Paula Aguiar*, Jean Ometto, Carlos Nobre, David Lapola, Claudio Almeida, Ima Vieira, João Vianei Soares, Regina Alvalá, Sassan Saatchi, Dalton Valeriano. "Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon". *Global Change Biology*, 18(11): 3346–3366, 2012.

A second software component of the project was the Geographic Data Mining Analyst (GeoDMA)[20]. This has algorithms for segmentation, feature extraction, feature selection, classification, landscape metrics and multi-temporal methods for change detection and analysis. GeoDMA uses decision-tree strategies adapted for spatial data mining. This software was used in the analysis of the occupation patterns in Amazonia by the project researchers.

3 Description of some of the project research results

In this section, we describe some of the project research results in more detail. The following descriptions are intended to illustrate our approach to the problem of modeling land use and land cover change in Amazonia.

3.1 The role of institutional arrangements in land change in Amazonia

One of the relevant results of the project was the development of an agent-based model for describing land change in a large frontier area in Amazônia: the São Felix do Xingu (SFX) region, an area of 100.000 km^2 in the South-East of the Pará state in Brazil, the place in Amazonia with the highest deforestation rate in the 1990s and 2000s[21]. The model captures large-scale land change during the 2000s and is used to build scenarios until 2020. The study area is shown in Figure 1.

[20] Thales Korting, Leila Fonseca*, Gilberto Câmara*, "GeoDMA - Geographic Data Mining Analyst". *Computers & Geosciences*, 57: 133–145, 2013.

[21] Sergio Costa, "Regional Scale Agent-Based Modelling of Land Change: Evolving Institutional Arrangements in Frontier Areas". PhD dissertation in Computer Science, INPE, 2012. Advisors: Gilberto Câmara* and Ana Paula Aguiar*.

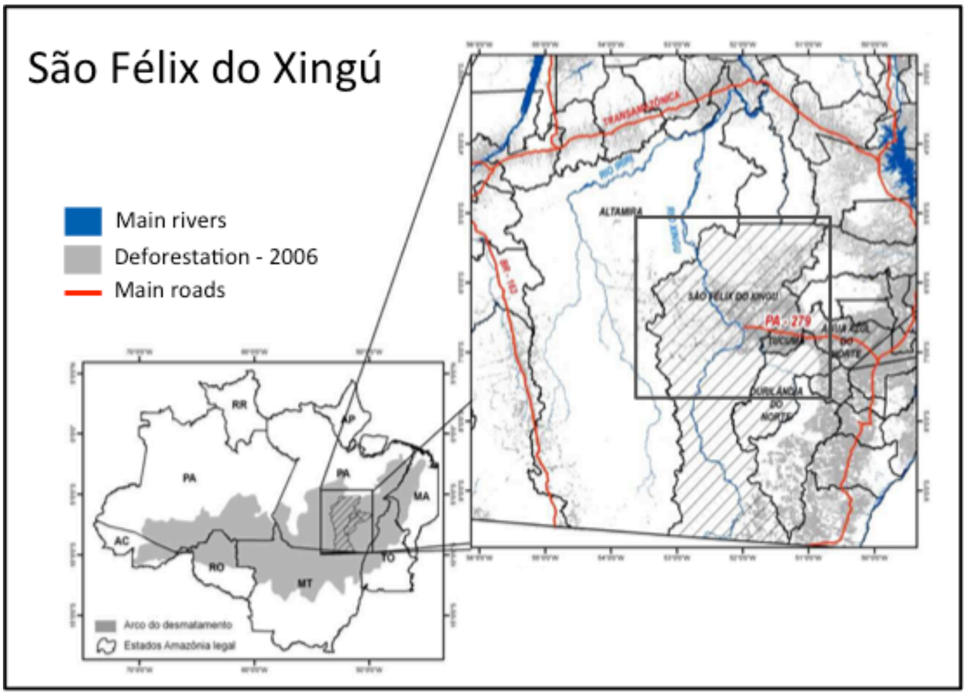

Figure 1. Study area: São Félix do Xingú, Tucumã and Ourilandia do Norte.

The region's population increased from 2,300 people in 1970 to 150,000 in 2010, and cattle heads soared from 190 to 2,500,000, accumulated deforestation in the region reached 20,500 km^2 in 2010. The number of farms grew from 282 in 1985 to 7,800 in 2007.

The work proposes an agent-based model (ABM) that captures the decision-making model of large and small farmers and the impact of the population migration to the area. The ABM balances endogenous behavior (*agents autonomous interactions*) with exogenous driving forces (*changes in government land policy*). One of the key concepts in the model is the idea of *institutional arrangements* that capture the rules and norms followed by agents. Considering the historical evolution of the São Felix region, we defined four institutional arrangements for the period of 1970 to 2010:

- *Government-induced occupation* (1970-1985): prevalent during the military regime, when the government encouraged people to occupy Amazonia.
- *Private capitalist occupation* (1985-1997): Occupation in Amazonia was led by arrangements involving local groups of farmers, capitalists

and politicians, with limited intervention from the Federal Government.

- *Beef marketing chain organization* (1997-2005): Starting in 1996, there was a renewal of public credits for cattle production that reinforced the effects on land change.
- *Deforestation control* (2005-2010)*:* From 2005 onwards, the Federal Government set up a combined effort of improved satellite monitoring, increased law enforcement, and creation of protected

The ABM for the São Felix do Xingu has the following components:

a) A *support capacity* submodel, that captures the capacity of the land to support extensive cattle raising.
b) A *frontier occupation* submodel, that represents the way the agents move from established areas to the frontier, grabbing new land and causing deforestation.
c) A *pasture creation* submodel, that captures how farmers manage their land for cattle raising.
d) A *reforestation* submodel, that represents the actions the farmers take to restore forest land.
e) A *land market* submodel, that simulates buying and selling of farms.

The authors ran a simulation, that starting from 1970, tried to reproduce the different institutional arrangements from 1997 until 2010. The results are shown in Figure 2, which compares the simulated deforestation patterns to the actual patterns measured by the PRODES system. The model was able to provide a reasonable account of the occupation process in São Felix. The model shows how the land market, the moving frontier and the institutional arrangements operate in shaping the evolution of deforestation in São Felix.

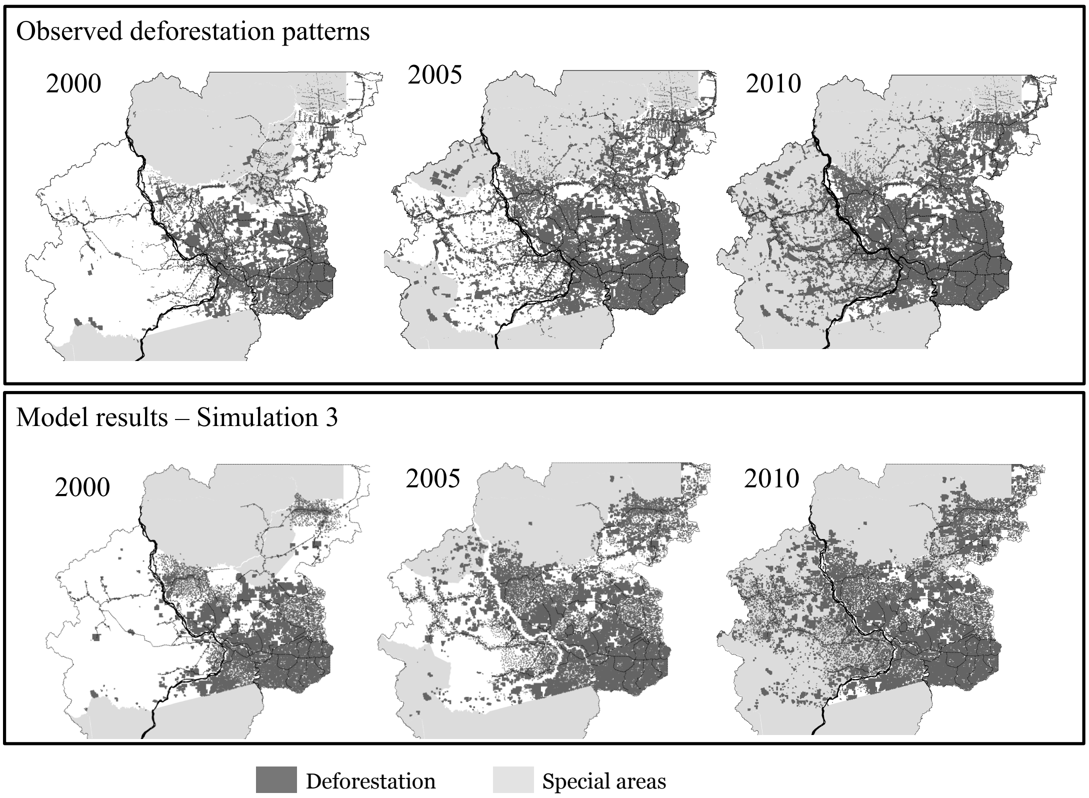

Figure 2. Comparison of observed deforestation patters (top) with results from model simulation S3 for 2000, 2005 and 2010 (bottom).

3.2 Statistical Analysis of Driving forces of Deforestation in Amazonia

This work was carried out on the context of a PhD thesis by Giovana Mira de Espindola, advised by Gilberto Câmara, Ana Paula Aguiar and Leila Fonseca, three of the project's leading investigators. The results of the thesis have been published in the scientific literature[22]. The thesis used spatio-temporal statistics to study determinant factors of land use change. We broke up deforestation in 1997 and 2007 into the main agricultural uses – pasture, temporary and permanent agriculture. To do this, we combined deforestation maps from INPE with census information from IBGE. We took the agricultural area for each city from the deforestation maps and the proportion of land use from the census data.

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22 Giovana Espindola, Ana Paula Aguiar, Edzer Pebesma, Gilberto Câmara, Leila Fonseca, 2012. "Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data". Applied Geography, 32(2):240-252.

The data included 30 explanatory variables grouped into four main types: access to markets, public policy, agrarian structure, and environment. As 'access to markets' variables, we took *distance to roads*, *distance to urban centers*, *distance to wood extraction distance to mineral deposits, distance to external markets*. The 'public policy' variables are *number of settled families*, *protected areas* and *indigenous lands*. The 'agrarian structure' data uses the proportion of small (< 200 ha), medium (200 to 1000 ha) and large (> 1000 ha) farms. The 'environment' data captures conditions such as *soil fertility* and *climate*. Land use data is taken as dependent (proportions of deforestation, pasture, temporary agriculture and permanent agriculture).

The regression models for deforestation in 1997 and 2007 show some important changes in the patterns of human occupation in the Brazilian Amazon. They are summarized in Figure 2 showing the relative influence of each factor, with 95% confidence intervals. The confidence intervals were used to infer which determinant factors changed from 1996/1997 to 2006/2007.

In both models, *distance to wood extraction*, *distance to rivers*, *protected areas, fertility* and *humidity index* did not change their influence from 1997 and 2007. *Connection to national markets* and *high fertility* changed little between these years. *Distance to roads* was more influential in 1997 than in 2007, suggesting that the influence of roads in deforestation decreased. The *number of settled families* influences deforestation. This influence increased in 2007, since the number of settlements increased during the 2000s. Finally, *indigenous lands* were crucial in preventing deforestation in areas of high population pressure.

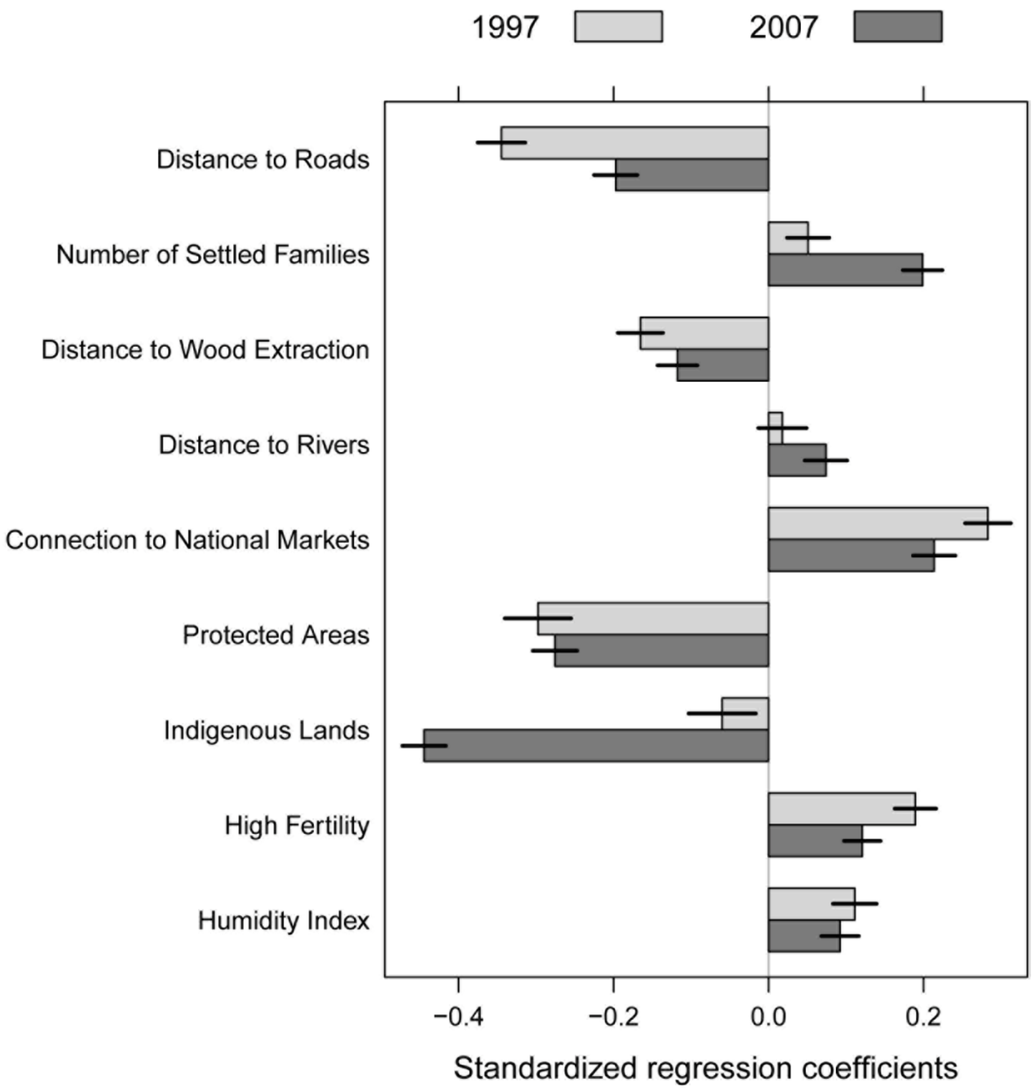

Figure 3 – Standardized regression coefficients for deforestation in the *roads and settlements* model for 1997 and 2007 with 95% confidence intervals.

3.3 Evaluation of land use models: a critical analysis

In a recent paper published in the journal “Land Use Policy”[23], we analysed several models that have been proposed to explore future trajectories of land use and cover change, particularly in the Amazon. We review and analyze the general structure of the land use models that have most recently been used to explore land use change in the Amazon, seeking to investigate methodological factors that could explain the divergence between the observed and projected rates, paying special attention to the land demand

[23] Eloi Dalla-Nora, Ana Aguiar, David Lapola, Geert Woltjer, 2014. “Why have land use change models for the Amazon failed to capture the amount of deforestation over the last decade?”, Land Use Policy, 39, pp. 403–411.

calculations. We found out that, despite the remarkable development of these tools, model results are still surrounded by uncertainties.

Figure

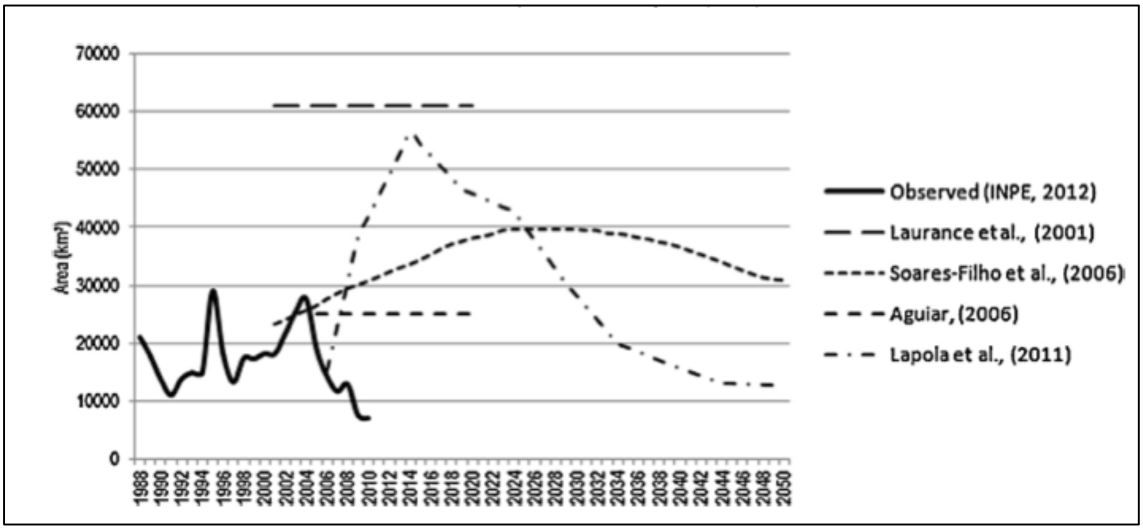

Figure 4 - Yearly forest loss area observed (2000–2010) and projected (2000–2050) for the Amazon in baseline trajectories.

As shown in Figure 4, none of the model projections available in the literature plausibly captured the overall trajectory of land use and cover change that has been observed in the Amazon over the last decade. Comparing modeling exercises developed for the Amazon we can identify two main approaches for land demand estimates: (i) the global approach and (ii) the intra-regional approach.

In the global approach, the land demand calculation is based primarily on the dynamics of global driving factors, such as economic growth, population growth, per capita consumption of agricultural products and international trade policies. This approach also includes biophysical aspects, such as climatic and agricultural aptitude conditions in the land demand calculation. The estimates of agricultural and livestock production are calculated from partial equilibrium global economic models, which use projections of economic and demographic growth. The global approach also allows the inclusion in the land demand calculation of political (trade barriers, subsidies) and technological (management practices, conversion efficiency) factors which are sometimes expressed only indirectly through changes in prices or productivity.

In the intra-regional approach, land demand is calculated based on the dynamics of local and regional factors, such as the distance to roads and other infrastructure projects (existing and planned) and the presence of constraints (primarily protected areas). In most cases, this approach also includes in the land demand calculation a baseline factor that is related to historical deforestation averages, over temporal horizons ranging from 5 to 25 years ago.

Thus, in the intra-regional approach the land demand calculation does not directly include any form of international pressure or productivity factors. The global approach, in turn, does not capture the dynamics and magnitude of intra-regional drivers in the definition of future land demand rates for the Amazon. These limitations prevent land use models from fully representing the forces that shape the dynamics of the region. These modeling exercises were also quite simplistic regarding the formulation of their scenario since institutional changes (the social and governmental reaction against high deforestations rates) were never considered.

Most land use models used in modeling exercises for the Amazon present are two separate submodles for land demand and land allocation (in the real world, they are interdependent). This division tries to capture the difference between the proximate causes of deforestation and the underlying driving factors. The proximate causes that are directly linked to the land use and cover change pattern (soil fertility, topography, infrastructure projects, etc.). The underlying driving factor are economic (price of agricultural commodities, access to rural credit), institutional (environmental policies, trade agreements) and technological (management practices, conversion efficiency) factors.

However, in the case of Amazonia, institutional factors and public policies play a key role. If Amazon deforestation was purely a result of price movements and other economic factors, we would expect that the slowdown in deforestation would be conjunctural and temporary, that is, deforestation would fluctuate according to the economic cycle, which did not actually occur. In this sense, regional policies adopted from 2004 have played an important role in the maintenance of the deforestation slowdown process. The effectiveness of regional policies generated a greater demand by producers and civil society for the regulation of their activities, which seems to have been decisive for the immediate reduction of deforestation rates observed over the last decade in the Amazon. Finally, it also reinforces the idea that Amazonian land cover change dynamics depend significantly on the behavior of local and regional factors along with intentional markets, which still need to be better understood and addressed in land use models.

The complex nature of the land use system in the Amazon indicates the need to adopt an innovative modeling framework to represent the forces that shape land use dynamics in this region. Sound land use models are useful for representing plausible ways in which the future could unfold in the context of scenario development, and explore the effects of changes in certain factors. In this sense, the integra- tion of flexible economic models and regional spatially explicit land use models is a possible way to increase the internal consistency of the modeling exercises and ultimately enhance their potential to represent future scenarios and support decision making.

3.4 Assessment of Performance of Land Change Models for Amazonia

In a companion work to the paper published in "Land Use Policy" and discussed in the previous sections, we evaluation of the results of several models of deforestation in the Brazilian Amazon in an *ex-post* analysis[24].

We developed a goodness of fit metric that uses a multi-resolution approach to account for the scale-dependency of spatial patterns. We applied the proposed goodness of fit metric to evaluated two models that try

[24] Luiz Veras, Merret Buurman, Pedro Andrade, Gilberto Camara*, and Edzer Pebesma. "Measuring Allocation Errors in Land Change Models in Amazonia." Brazilian Symposium on Geoinformatics, 2013.

to predict deforestation in the Brazilian Amazon: The SimAmazonia model, developed by Soares-Filho et al., and the model developed by Laurance et al[25]. We evaluated model projections for the year 2011, taking the PRODES data provided by INPE (Brazilian National Space Research Institute) as the reference for observed deforestation.

SimAmazonia projects the deforestation in Amazonia in 2050, based on data from 2001. We estimated its results for 2011 using data provided by its authors. For our assessment, we took the Business-as-usual scenario (BAU) and the Governance scenario (GOV). The model by Laurance et al. projects deforestation in the Brazilian Amazonia in 2020 based on the data for 2000. It assumes a heavy impact of infrastructure projects that would lead to deforestation in Amazonia of 28% (optimistic scenario) or 42% (non-optimistic scenario) in 2020. The non-optimistic scenario assumes larger degraded areas close to roads and rivers and more deforestation in conservation areas.

We also used a neighborhood model as an example of the simplest possible land change model for Amazonia. The model has a single assumption: the potential for change in one year is the average deforestation of the neighboring cells for the previous year.

The demand for deforestation in all models is the actual total deforestation given by PRODES. The first two models originally projected higher demand compared to the PRODES estimates. We reimplemented such models in order to take into account the differences in the demand. Figure 5 shows the goodness of fit plotted against sampling window size. We see the differences between the model performances persist over many resolutions. The goodness of fit values increase slowly with increasing window size (note the logarithmic scale of the x axis).

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[25] Soares-Filho, B., et al., Modelling conservation in the Amazon basin. Nature, 2006. 440(7083): p. 520-523.
Laurance, W., et al., The future of the Brazilian Amazon. Science, 2001. 291: p. 438-439.

The models allocate a lot of change in wrong regions. Both SimAmazonia models have a similar performance. The Laurance scenarios project most of the change in the wrong places. Even with sampling windows of size of 32 by 32 cells (800 by 800km), the Laurance models have a fit of only approximately 50%. The simple neighborhood model performs almost as well as the SimAmazonia models and much better than the Laurance models. Even the best model considered in our study allocates only about 60% of the change correctly.

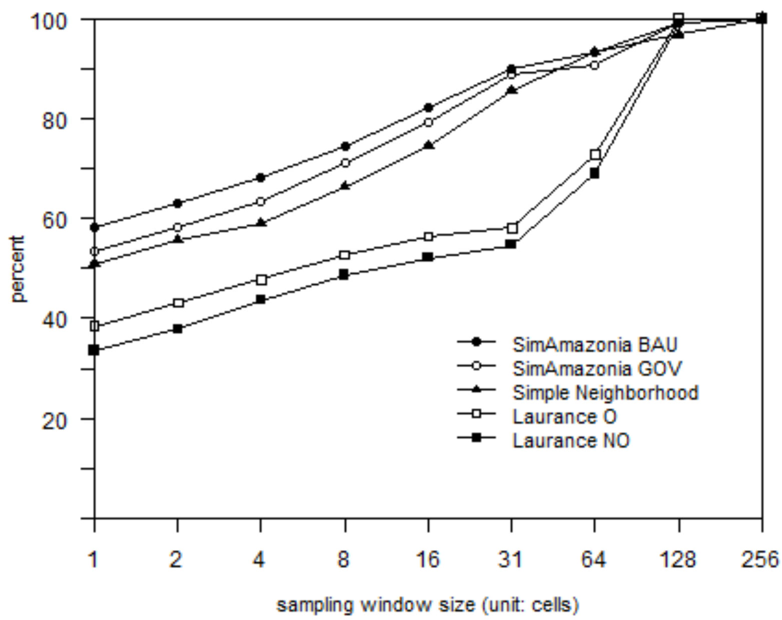


Figure 5: The goodness of fit of the different models plotted against sampling window size (logarithmic scale). The largest window is 256 by 256 cells. As it covers the whole cell space, which is 134 by 104 cells large, the goodness of fit is inevitably 100%.

We compare cell spaces of the deforestation as predicted by the models with the PRODES dataset in Figure 6. Because of their over-reliance on road infrastructure as the main factor for deforestation, the Laurance models allocate much change in the wrong places and underestimate the effectiveness of protected areas. SimAmazonia captures most of the change close to existing deforested areas, but has a limited ability to predict how the frontier expands. It misses most of the deforestation around the Cuiabá-Santarém road (c) and predicted change close to Manaus (d), in Roraima (e) and in the North of Pará (f) that did not happen.

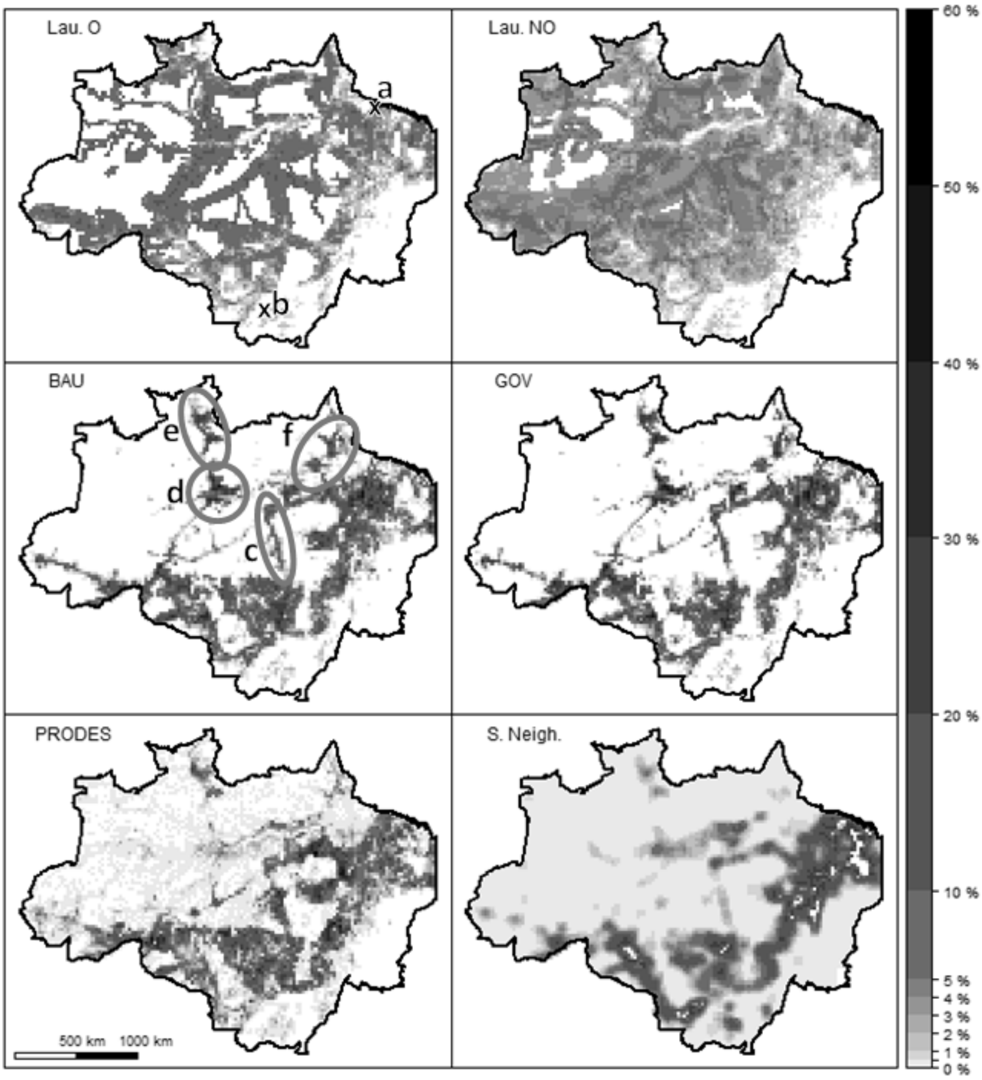


Figure 6: Maps of the area that was deforested in the years 2003-2011, according to PRODES data (lower left) and the model scenarios. The darker the cell's color, the higher the percentage of area deforested in that cell (values range from 0% to 60%).

3.5 Measurement and mapping of vegetation cover transformation

In the project, we worked on techniques to improve extraction of land change information from remote sensing images. Our results in the project have studied the combination of optical and radar data to map urban areas in Amazonia[26]. Our results point out that the complex urban–rural landscape patterns in Amazonia cannot be effectively well mapped by LANDSAT TM

[26] Dengsheng Lu, Guiying Li, Emilio Moran, Mateus Batistella, and Corina Freitas*, "Mapping impervious surfaces with the integrated use of Landsat Thematic Mapper and radar data: A case study in an urban–rural landscape in the Brazilian Amazon." ISPRS Journal of Photogrammetry and Remote Sensing 66(6): 798-808, 2011.

multispectral images with 30 m spatial resolution. These urban-rural landscapes require image with 10 m spatial resolution or better.

Producing accurate image classification is a challenge, particularly in moist tropical regions, due to the complex biophysical environment and limitations of remote sensing data. In tropical regions, availability of optical data is limited by cloud cover, and radar data is not sensitive to clouds.. Radar and optical data are complementary and integrating them improves information extraction.

The paper compares parametric and non-parametric LUCC classification algorithms for these three study areas. The spectral signatures of remotely sensed data, for medium spatial resolution images, such as Landsat, are still the most important features in land use/cover classification. The authors conclude that parametric algorithms such as the maximum-likelihood classifier are not appropriate for LUCC when optical and radar images are combined. Advanced nonparametric classifiers, such as decision tree, evidential reasoning, or the knowledge-based approach, appear to be the best choices.

The comparison of LUCC classification methods for combined optical and radar images was futher explored in the GEOBIA 2012 paper[27]. In this paper, we compare the performance of per-pixel based parametric algorithms (maximum likelihood classification) with an object-based classifier. The study case is a region in Altamira, Pará, and the input data is a fusion image combining LANDSAT-TM optical data with ALOS PALSAR L-band radar data. The results point out that indicates that Landsat TM multispectral image provided better land use/cover classification than ALOS PALSAR L-band data. Integration of TM multispectral and PALSAR L-band data through the data fusion method is valuable for improving classification

[27] Dengsheng Lu, Guiying Li, Emilio Moran, Corina Freitas*, Luciano Dutra*, Sidnei Sant'Anna. A comparison of maximum likelihood classifier and object-based method for land-use/cover classification in the Brazilian Amazon based on multiple sensor datasets. In: Geographic Object-Based Image Analysis, 2012, Rio de Janeiro. Proceedings of 4th GEOBIA, 2012. p. 20-24.

performance by about 5% when using the object-based classifier. When using a maximum-likehood classifier, combining TM multispectral and PALSAR-derived textural images as extra bands actually reduces classification performance (see Figure 6). The paper concludes that object-based classification is especially useful when higher spatial resolution images are available.

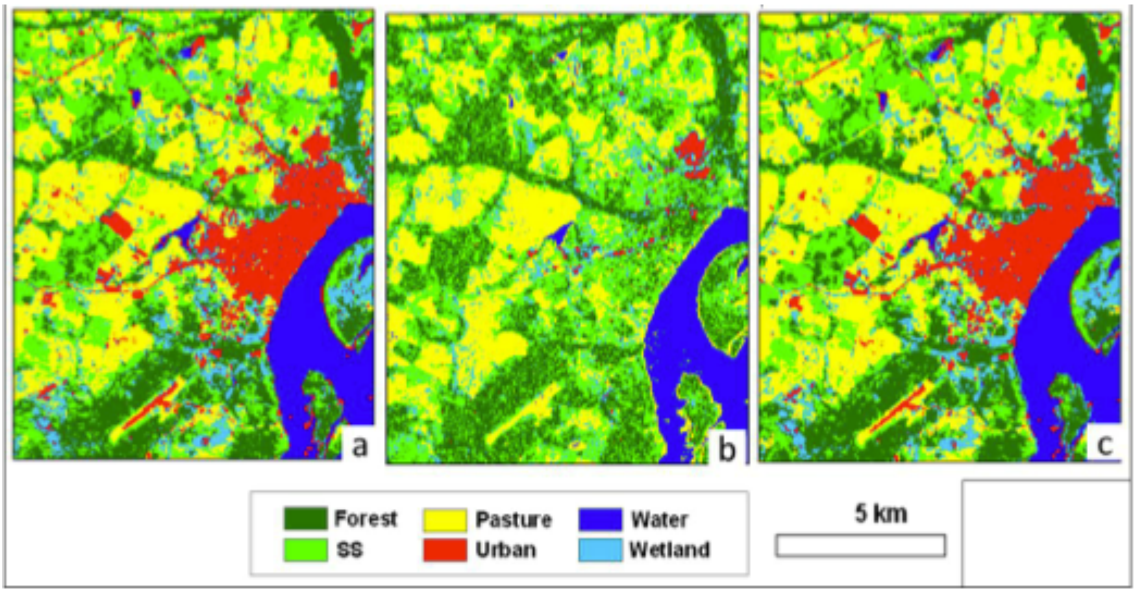
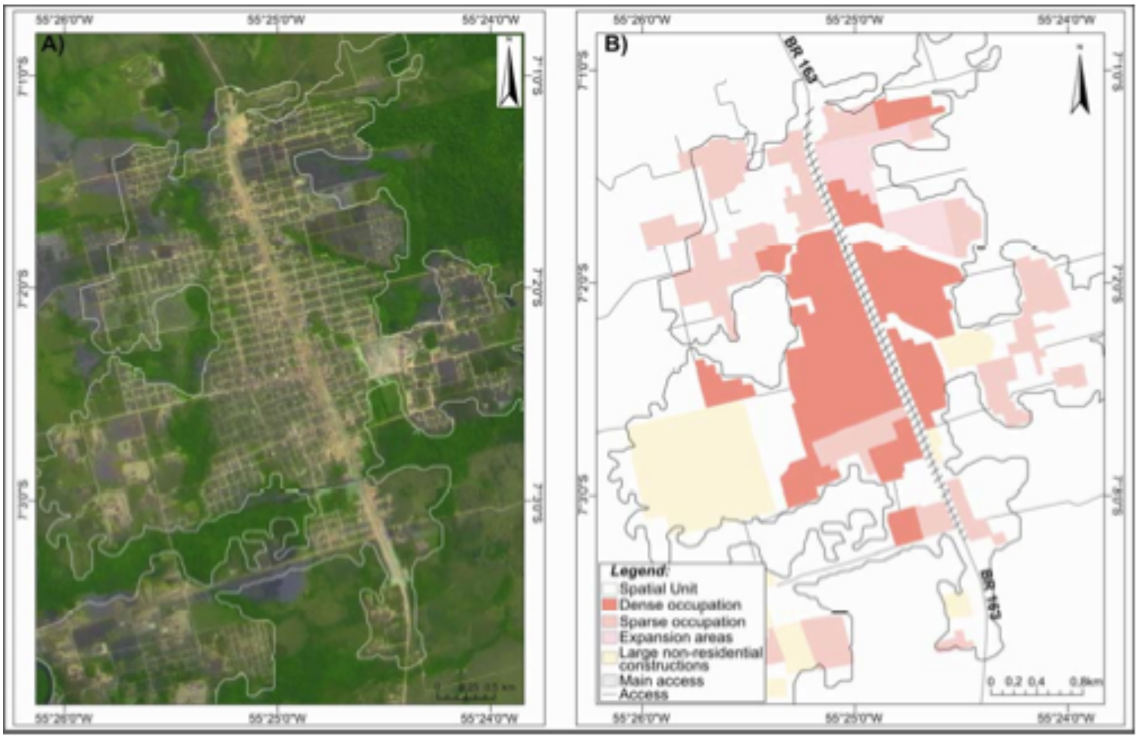


Figure 6. Comparison of classification results with per-pixel maximum-likelihood classification for the Altamira study area: (left) Landsat TM image; (middle) PALSAR L-band data; (right) TM multispectral and PALSAR L-band HH fusion image with the wavelet-merging technique.

3.6 Identifying Human Settlements in Amazonia

In the project, our research is based on the concept of extensive urban in Amazônia, where a large set of socio-spatial forms is considered, in the urban and in the rural area. This urban plays an important role influencing the changes in land use and cover. Land occupation starts by creating and expanding settlements, which serve as a basis for the land use activities. We used multi-resolution remote sensing data to identify and map human presence and activities in the Sustainable Forest District of Cuiabá-Santarém highway (BR-163)[28]. High-spatial-resolution CBERS-HRC images (2.5 m) merged with CBERS-CCD (images (20 m) were used to map spatial arrangements inside each populated unit, describing intra-urban characteristics. Using CBERS high-resolution images, we were able to identify different types of human occupation in the city of Novo Progresso, which is located on the BR-163 road, and is one of the main focus of deforestation in the region (Figure 7).



[28] Ana Paula Dal'Asta, Newton Brigatti, Silvana Amaral*, Maria Isabel Sobral Escada* and Antonio Miguel Monteiro. Identifying Spatial Units of Human Occupation in the Brazilian Amazon Using Landsat and CBERS Multi-Resolution Imagery. Remote Sensing, 4: 68-87, 2012.

Figure 7. Boundaries of the spatial units of human occupation obtained from Landsat TM for Novo Progresso over CBERS-CCD/HRC fused image (left) and spatial patterns mapping (right).

3.7 Relating rural and urban areas in Amazonia

One important concern we had in the project was to map the relationship between urban patterns and rural land use. One of our studies was focused on the evolution of the urban space and agricultural land in Santarém from 1990 to 2010[29]. The work had two parts. First, we identified the types of urban occupation in Santarém using remote sensing data. Then, we singled out the types of agricultural land use close to the city. Results are shown in Table 1 and Table 2.

Table 1. Types of urban occupation in Santarém

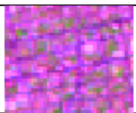
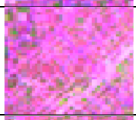
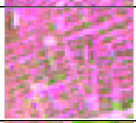
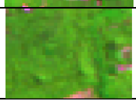
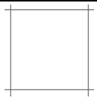
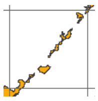
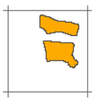
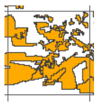
Padrão	Tipologia	Descrição
	*Dense occupation*	> 80% of built space; pavements; vegetation < 15%; clear street definition.
	*Medium urban density*	50 – 80% of built space; vegetation from 20 to 40% of area; clear street definition.
	*Low urban density*	30 – 50% of built space; vegetation from 40 to 60% of area; clear street definition.
	*Urban Expansion*	Less than 30% of built space; vegetation from 40% to 80% of area; much soil change.
	*Business and institutional area*	Áreas with industries and large buildings.
	*Vegetation*	>80% of trees

Table 2. Types of agricultural land near Santarém.

[29] Ana Paula D'Asta, Isabel Escada, Silvana Amaral, Miguel Monteiro. Evolução do arranjo espacial urbano e das terras agrícolas no entorno de Santarém (Pará) no período de 1990 a 2010: Uma análise integrada baseada em sensoriamento remoto e espaços celulares. In: XVI Brazilian Symposium on Remote Sensing (SBSR), Foz de Iguaçu, 2013.

Pattern	Type	Description	Occupation pattern
	*Continuous*	Wetlands, urban areas , forest, secondary vegetation.	Non agricultural areas
	*Diffuse*	Small spot; Isolated occupation Low to medium density	Shifting cultivation; small-scale agriculture.
	*Linear*	Elongated areas, showing a direction of occupation	Road-associated agriculture (new settlements in early stages), riverine population
	*Geometric*	Regular geometric forms, with medium to large size. Sparse forms, with medium to small density.	Mechanized agriculture or large-scale cattle raising, associated to mid and large size farmers.
	*Continuous Geometric*	Regular geometric forms, continuously spread with high density.	Mechanized agriculture or large-scale cattle raising, associated to mid and large size farmers.
	*Mixed areas*	Irregular forms associated to geometric forms; medium to high density.	Mechanized agriculture or large-scale cattle raising, combined with small-scale production.

Based on this typology, we obtained two relevant results using the GeoDMA software. First, we found out that there was a densification of the urban occupation in Santarém. The expansion of the urban areas from 1991 to 2010 was less than 5 km^2, while the population increased by almost 30,000 people. We also found out a marked land concentration. Figure 11 shows the patterns of agricultural land change near Santarém in 1990, 1999 and 2010. We can see an increase of large-scale agriculture associated to soybean production and large-scale cattle raising. In this period, Santarém became an important port for export soybean and meat, which is clearly motivating a major agricultural expansion in the area.

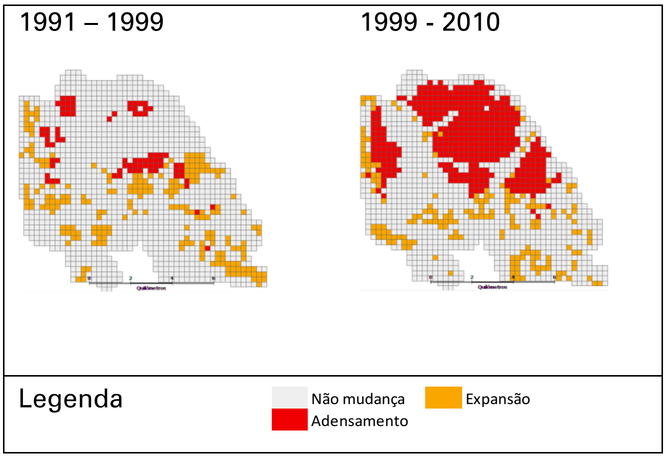


Figure 8. Urban densification in Santarém (1991-2000). Dense urban regions shown in red. Expansion areas in yellow.

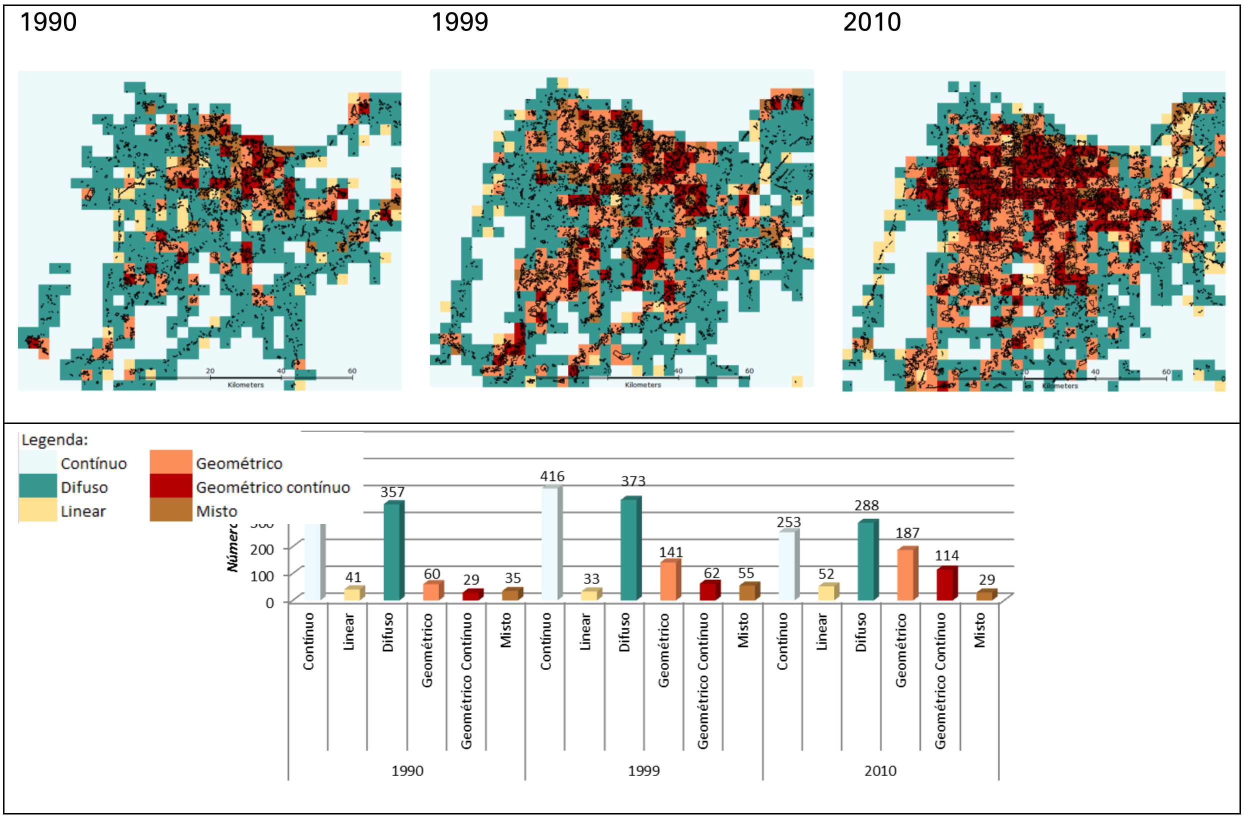


Figure 9. Agricultural land patterns in Santarém –1990, 1999 e 2010 (light blue – no agriculture; green – diffuse; yellow – linear; light red – geometric; dark red – continuous geometric; brown – mixed áreas).

3.8 GeoDMA - Geographic Data Mining Analyst

GeoDMA (Geographical Data Mining Analyst) is a software for remote sensing data mining. The main motivation of GeoDMA is that there is much information available in remote sensing images which is not used by traditional image processing statistical classifiers. In particular, information on shape, patterns and spatio-temporal trends is not used. To use this information, GeoDMA applies data mining techniques to remote sensing imagery. The software associates landscape ecology metrics to land change patterns. Then, it uses data mining algorithms to classify the patterns. GeoDMA provides simulation methods to assess the accuracy of process models as well as tools for spatio-temporal analysis, including a visualization scheme for temporal profiles that helps users to describe patterns in cyclic events.

GeoDMA implements image segmentation, extraction and selection of image segment attributes, region-based classification and exploratory data analysis tools. GeoDMA works as a plugin of the free GIS software TerraView, developed by INPE and available at www.terralib.org. It uses the geographical data handling and visualization structure provided by TerraView. Both systems were developed using the open source TerraLib library. We have used GeoDMA to describe land change patterns and trajectories in Amazonia, as outlined in the previous sections. GeoDMA is available at http://geodma.sourceforge.net/. The development of GeoDMA has been supported by FAPESP thorugh the LUA project.

The project supported the GeoDMA software, which was the basis for a PhD dissertation at INPE[30] and a paper accepted at an important journal[31]. We

[30] Thales Korting, "GeoDMA: a toolbox integrating data mining with object-based and multi-temporal analysis of satellite remotely sensed imagery". PhD dissertation in Remote Sensing, INPE, 2012. Advisors: Leila Fonseca and Gilberto Camara.

[31] Thales Korting, Leila Fonseca, Gilberto Câmara, "GeoDMA - Geographic Data Mining Analyst: a framework for GIScience". *Computers & Geosciences*, 57: 133–145, 2013.

also extended GeoDMA to work with time series, including classification methods for time series and a specific GUI for multi-temporal analysis.

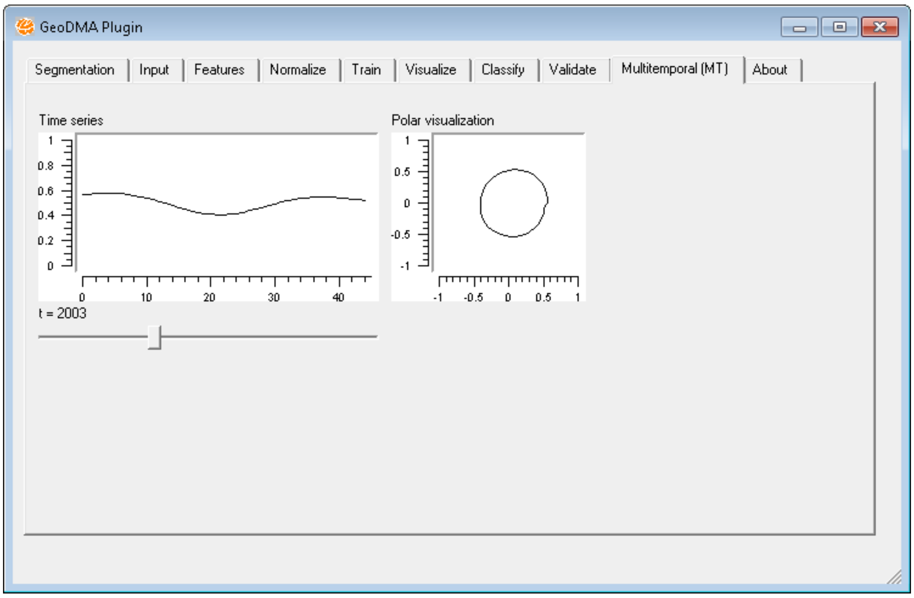


Figure 12. GUI for multi-temporal analysis in GeoDMA.

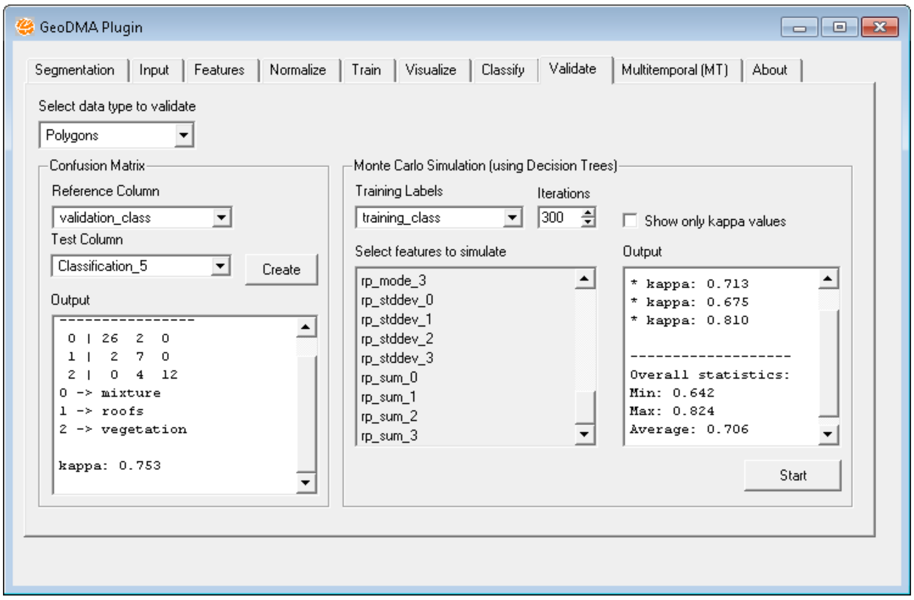


Figure 13. Simulation methods for accuracy assessment in GeoDMA.

To date, more than 20 scientific papers have already used the GeoDMA software for identifying land change and urban patterns, always with positive results. As GeoDMA evolves, we hope it will become a well-used tool for change analysis.

3.9 TerraME

Modeling interactions between social and natural systems is a hard task. It involves collecting data, building up a conceptual approach, implementing, calibrating, simulating, validating, and possibly repeating these steps again and again. There are different conceptual approaches proposed in the literature to tackle this problem. However, for complex problems it is better to combine different approaches, giving rise to a need for flexible and extensible frameworks for modeling nature-society interactions.

Given that most of the scientific problems we face in the LUA/IAM project involve understanding and modeling human-nature interaction, the project supported the development of TerraME. It is an open source toolbox that supports multi-paradigm and multi-scale modeling of coupled human-environmental systems. TerraME is a software for developing multiscale spatially explicit models It enables models that combine agent-based, cellular automata, system dynamics, and discrete event simulation paradigms. TerraME has a GIS interface for managing real-world geospatial data. The simulation language used by TerraME is an extension of Lua, a high-level scripting language. TerraME extends Lua with data types and functions for modeling and simulating human-enviroment systems[32].

Development of TerraME started in 2006, as part of Tiago Carneiro's PhD at INPE. Pedro Andrade and Eva Moreira, as part of their PhDs, made further advances. The LUA project supported major developments in TerraME:

a) Release of TerraME versions 1.1, 1.2 and 1.3.
b) Full implementation of TerraME Observer, the visualization component of the TerraME.

[32] Tiago Carneiro, Pedro Andrade, Gilberto Câmara, Antônio Miguel Monteiro, Rodrigo Reis Pereira, "TerraME: an extensible toolbox for modelling nature-society interactions". Enviromental Modelling and Software, 46: 104-117, 2013.

c) Significant improvements in agent-based modeling in TerraME, following the experience of developing a model for deforestation in Amazonia.

The visualization mechanism is structured according to the Observer software design pattern. Graphical interfaces for scientific visualization are called *observers* and present real-time changes in the internal state of any TerraME object. In this context, each instance of a model component is called *subject*. As Figures 1 illustrates, several observers can be linked to a single subject, so that the evolving state of a subject can be analyzed simultaneously in many ways. Changes in a subject are explicitly notified to the observers in the model source code. This assures that only consistent states will be rendered by the observers and gives complete control to the modeler to decide in which changes he is interested in. When notified, each observer updates itself requesting information about the internal state of its subject. Then, the state is serialized and transferred to the observers to render the graphical interface. The work was presented in a scientific paper[33].

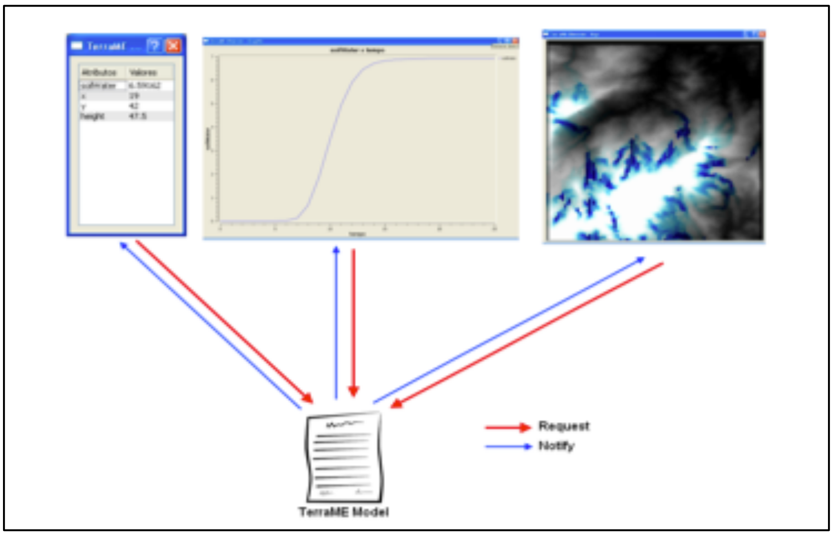


Figure 14. Visualization in TerraME is structured according to the Observer software design pattern.

[33] Antonio Rodrigues, Tiago Carneiro, Pedro Andrade*. TerraME Observer: Extensible real-time visualizations of dynamic spatial models. In: GeoInfo 2012, Campos do Jordão, 2012.

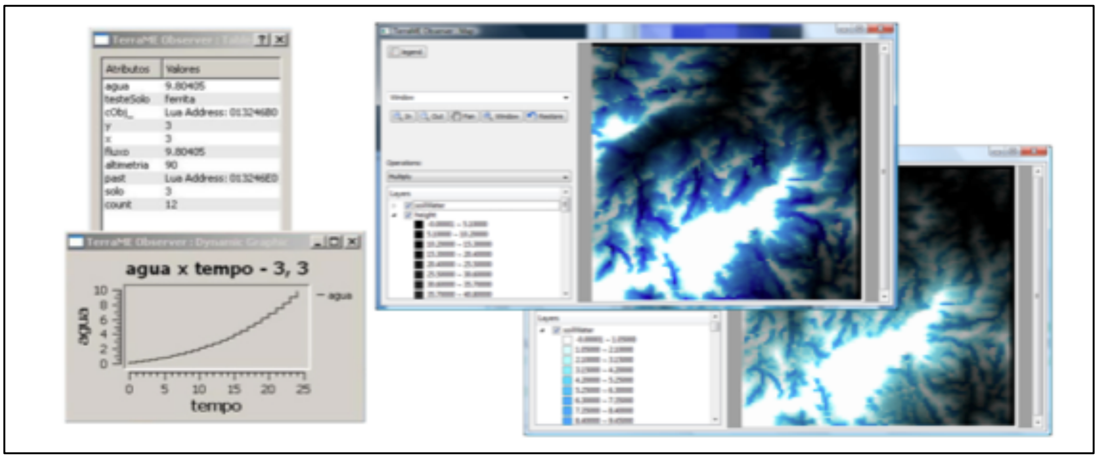


Figure 15. Different types of TerraME observers: dynamic tables, charts and maps.

3.10 INPE-EM: Emissions modelling

INPE-EM is a TerraME extension of calculating emissions related to land change. The INPE-EM model was described in the LUA Second Project Report and has been published in an important scientific journal[34]. INPE-EM model was used for estimating greenhouse gas emissions from cattle raising in Brazil, which was published as a scientific paper[35].

The study estimated, for the first time, the greenhouse gas emissions associated with cattle raising in Brazil, focusing on the period from 2003 to 2008 and the three principal sources: 1) portion of deforestation resulting in pasture establishment and subsequent burning of felled vegetation; 2) pasture burning; and 3) bovine enteric fermentation. Deforestation for pasture establishment was only considered for the Amazon and Cerrado. Emissions from pasture burning and enteric fermentation were accounted for the entire country. The consolidated emissions estimate lies between approximately 813 Mt CO_2eq in 2008 (smallest value) and approximately 1,090 Mt CO_2eq in 2003 (greatest value). The total emissions associated with

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[34] Ana Paula Aguiar, Jean Ometto, et al. Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon. *Global Change Biology*, 18(11): 3346–3366, 2012.

[35] Mercedes Bustamante, Carlos Nobre, Roberto Smeraldi, Ana Aguiar*, Luis Barioni, Laerte Ferreira, Karla Longo, Peter May, Alexandre Pinto, Jean Ometto. Estimating greenhouse gas emissions from cattle raising in Brazil. *Climatic Change*, 115(3-4):559-577, 2012.

Amazon cattle ranching ranged from 499 to 775 Mt CO_2eq, that of the Cerrado from 229 to 231 Mt CO_2eq, and that of the rest of the country between 84 and 87 Mt CO_2eq. The full set of emissions originating from cattle raising is responsible for approximately half of all Brazilian emissions (estimated to be approximately 1,055 Mt CO_2eq in 2005), even without considering cattle related sources not explicitly estimated in this study, such as energy use for transport and refrigeration along the beef and derivatives supply chain.

The paper identified some priority action areas to effectively address these sources of emissions:

1. Mitigation potentials in the Brazilian cattle industry are significant and do not imply cutting back on current production. Key mitigation sources should include reduction of deforestation and regeneration of secondary forest, reduction in enteric fermentation, recuperation of degraded pasture and soils and elimination of fire in pasture management.
2. Substantial investment in quality of pasture and related technologies such as, among others, rotational grazing or introduction of legume pasture, is essential to all forms of mitigation.
3. Methane emissions by enteric fermentation can be reduced significantly as a result of increased productivity, including genetic improvement in the herd, use of supplemental rations and provision of mineral salt, which allow for faster fattening and higher survival rates resulting in a much shorter average lifespan in relation to current standards of extensive ranching.

ANNEX 1

Full List of Scientific Results

In this section we present the full list the scientific results achieved in the project. Project researchers involved in the thesis and papers are highlighted by an asterisk (*).

PhD Dissertations

1 Eliana Pantaleao, "Análise de cenários para classificação de dados de sensoriamento remoto usando otimização multiobjetivo e hierarquia de classes." (Classification of remote sensing images using multi-objective optimization). PhD dissertation in Computer Science, INPE, 2012. Advisor: Luciano Vieira Dutra*.

2 Sergio Costa, "Regional Scale Agent-Based Modelling of Land Change: Evolving Institutional Arrangements in Frontier Areas". PhD dissertation in Computer Science, INPE, 2012. Advisors: Gilberto Câmara* and Ana Paula Aguiar*.

3 Carolina Pinho, "Análise de redes de localidades ribeirinhas amazônicas no tecido urbano estendido" (The role of Amazonian settlements in the urban network: a proposal based on network analysis). PhD dissertation in Remote Sensing, INPE, 2012. Advisors: Leila Fonseca* and Silvana Amaral*.

4 Giovana Mira de Espindola, "Spatiotemporal Trends of Land Use Change in the Brazilian Amazon". PhD dissertation in Remote Sensing, INPE, 2012. Advisors: Leila Fonseca* and Gilberto Camara*.

5 Thales Korting, "GeoDMA: a toolbox integrating data mining with object-based and multi-temporal analysis of satellite remotely sensed imagery". PhD dissertation in Remote Sensing, INPE, 2012. Advisors: Leila Fonseca* and Gilberto Câmara*.

6 Karine Reis Ferreira, "An Algebra for Spatiotemporal Data: From Observations to Events". PhD dissertation in Computer Science, INPE, 2012. Advisors: Gilberto Camara* and Antônio Miguel Vieira Monteiro.

7 Gilberto Ribeiro de Queiroz, "CellDB: Uma Arquitetura de Acesso a Dados para Modelagem Ambiental em Grande Escala Baseados em Espaços Celulares" (CellDB: a data access architecture for large-scale environmental modeling in cell spaces). PhD dissertation in Computer Science, INPE, 2012. Advisors: Gilberto Camara* and Antônio Miguel Vieira Monteiro.

8 Ramon Morais de Freitas, "Estudos de métodos computacionais para visualização e caracterização do uso e cobertura da terra utilizando imagens de sensoriamento remoto" (Computational methods for visulisation and idenficaton of land use and land cover using remote sensing images). PhD dissertation in Computer Science, INPE, 2012. Advisor: Yosio Edemir Shimabukuro.

9 André de Lima, "Influência da cobertura da terra na extensão e configuração espacial de áreas queimadas em anos de seca extrema na Amazônia Oriental" (Influence of land cover in the extension and spatial configuration of burned areas in extreme drought years in Eastern Amazonia). PhD dissertation in Remote Sensing, INPE, 2013. Advisor: Yosio Shimabukuro*.

10 Fabrício Brito Silva, "Modelagem da Produtividade Primária Bruta na Bacia Amazônica" (Modelling Gross Primary Productivity in Amazonia") . PhD dissertation in Remote Sensing, INPE, 2013. Advisor: Yosio Shimabukuro*.

11 Marcus Saldanha, "Um segmentador multinível para imagens SAR polarimétricas baseado na distribuição Wishart" (Multilevel segmentation in SAR images). PhD dissertation in Computer Science, INPE, 2013. Advisor: Corina da Costa Freitas*.

12 Rogerio Negri. "Maquina de Vetores de Suporte Adaptativa ao Contexto: Formalização e Aplicações em Sensoriamento Remoto" (Adaptative Support Vector Machine Algorithm). PhD dissertation in Computer Science, INPE, 2013. Advisor: Luciano Vieira Dutra*.

13 Wagner Silva, Classificação de regiões de imagens utilizando testes de hipótese baseados em distâncias estocásticas: aplicações a dados

polarimétricos (Region classifier using stochastic distances). PhD dissertation in Remote Sensing, INPE, 2013. Advisor: Corina da Costa Freitas*.

MSc Thesis

1 Saito, E. A; Caracterização de Trajetórias de Padrões de Ocupação Humana na Amazônia Legal por meio de Mineração de Dados. MSc thesis in Remote Sensing, INPE, 2010. Advisors: Leila Fonseca* and Maria Isabel Sobral Escada*.

2 Ricardo Theophilo Folhes; Cenários de Mudanças no Uso e Cobertura da Terra na Amazônia: uma abordagem participativa em um assentamento agro-extrativista em Santarém. MSc thesis in Environmetal Science UFPA, 2010. Advisors: Ana Paula Aguiar*.

3 Gavlak, A. A. Padrões de mudança de cobertura da terra e dinâmica populacional no Distrito Florestal Sustentável da BR-163: população, espaço e ambiente. MSc thesis in Remote Sensing, INPE, 2011. Advisors: Maria Isabel Sobral Escada* and Antônio Miguel Vieira Monteiro.

4 Talita Oliveira Assis, "Modelagem de Processos de Mudanças de Uso da Terra" (Modelling Processes of Land Use Change). MsC thesis in Computer Science, INPE, 2012. Advisors: Gilberto Câmara* and Ana Paula Aguiar*.

5 Luciana de Oliveira Pereira, "Avaliação de métodos de integração de imagens ópticas e de radar para a classificação do uso e cobertura das terra na região Amazônica" (Evaluation of methods for integrating radar an optical images for classification of land use and land cover in Amazonia). MsC thesis in Remote Sensing, INPE, 2012. Advisors: Corina da Costa Freitas* and Sidnei Sant'Anna*.

6 Luiz Gustavo Veras, "Análise de erros de alocação de modelos de uso e cobertura da terra na Amazonia". Mestrado em Computação Aplicada, INPE (co-orientação com). Início: Março 2010. Fim: Maio 2013. Advisors: Gilberto Câmara* and Pedro Andrade-Neto*.

7 Merret Buurman, “Regionalisation of the Brazilian Amazon basin for improved land change modelling”. Master of Science in Geoinformatics, Institute for Geoinformatics, University of Münster, 2014. Advisors: Gilberto Câmara* and Edzer Pebesma.

3.11 Journal papers (published or in press)

2010

1 Pedro Alves, Silvana Amaral*, Maria Isabel Sobral Escada*, Antôno Miguel Vieira Monteiro, “Explorando as relações entre a dinâmica demográfica, estrutura econômica e mudanças no uso e cobertura da terra no sul do Pará: Lições para o distrito florestal sustentável da BR-163”. *Geografia (Rio* Claro), 35(1):165-182, 2010.

2 Luke Parry, Brett Day, Silvana Amaral*, and Carlos A. Peres. "Drivers of rural exodus from Amazonian headwaters." *Population and Environment* 32(2-3):137-176, 2010.

3 Luke Parry, Carlos A. Peres, Brett Day, and Silvana Amaral*. "Rural–urban migration brings conservation threats and opportunities to Amazonian watersheds." *Conservation Letters* 3(4): 251-259, 2010.

4 Luiz Aragão, and Yosio Shimabukuro*, "The incidence of fire in Amazonian forests with implications for REDD." *Science* 328(5983) 1275-1278, 2010.

5 Aboud-Neta, S. R. ; Freitas, C. C. ; Dutra, L. V., "Uso de imagens ALOS/Palsar multipolarizadas para detecção de incremento de desflorestamento na Amazonia, *Revista Brasileira de Cartografia* (Online), p. 417, vol. 62, 2010.

2011

6 Guiying Li, Emilio Moran, Luciano Dutra*, and Mateus Batistella. "A comparison of multisensor integration methods for land cover classification in the Brazilian Amazon." *GIScience & Remote Sensing* 48(3):345-370, 2011.

7 Dengsheng Lu, Guiying Li, Emilio Moran, Mateus Batistella, and Corina Freitas*, "Mapping impervious surfaces with the integrated use of Landsat Thematic Mapper and radar data: A case study in an urban–rural landscape in the Brazilian Amazon." *ISPRS Journal of Photogrammetry and Remote Sensing* 66(6): 798-808, 2011.

8 Liana Anderson, Luiz Aragao, Yosio Shimabukuro*, Samuel Almeida, and Alfredo Huete. "Fraction images for monitoring intra-annual phenology of different vegetation physiognomies in Amazonia." *International Journal of Remote Sensing* 32(2): 387-408, 2011.

9 Egídio Arai, Yosio Shimabukuro*, Gabriel Pereira, and Nandamudi Vijaykumar. "A Multi-Resolution Multi-Temporal Technique for Detecting and Mapping Deforestation in the Brazilian Amazon Rainforest." *Remote Sensing* 3(9):1943-1956, 2011.

10 Eduardo Maeda, Gustavo Arcoverde, Petri Pellikka, and Yosio Shimabukuro*. "Fire risk assessment in the Brazilian Amazon using Modis imagery and change vector analysis." *Applied Geography* 31(1):76-84, 2011.

11 Ramón Freitas, Egidio Arai, Marcos Adami, Arley Ferreira, Fernando Sato, Yosio Shimabukuro*, Reinaldo Rosa, Liana Anderson, and Bernardo Rudorff. "Virtual laboratory of remote sensing time series: visualization of MODIS EVI2 data set over South America." *Journal of Computational Interdisciplinary Sciences* 2(1): 57-68, 2011.

12 Jean Ometto, Ana Paula Aguiar*, and Luiz Martinelli. "Amazon deforestation in Brazil: effects, drivers and challenges." *Carbon Management* 2(5):575-585, 2011.

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ANNEXES

Reports from Project Scholarship Students

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