Land change modeling and institutional factors: heterogeneous rules of territory use in the Brazilian Amazonia

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Abstract. *Land changes are determined by a complex web of biophysical and socio-economic factors that interact in time and space, in different historical and geographical contexts, creating different trajectories of change. It is people's response to economic opportunities mediated by institutional factors that drives changes. In this paper we discuss how to incorporate such institutional land tenure categories in land change models. Our hypothesis is that this is an essential step in the direction of constructing regional models to represent the heterogeneity of actors and processes. We implemented the conceptual proposal using the TerraME modeling Environment. Through a case study we analyze how the existence of different rules of territory use affects the landscape dynamics at the regional level.*

1. Introduction

Land change studies have a fundamental role in environmental research, since they establish a link between human activities and environmental systems. Land changes are determined by a complex web of biophysical and socio-economic factors that interact in time and space, in different historical and geographical contexts, creating different trajectories of change. Decisions that influence land change are made at different levels of organization (individual, household, community, nations, international/environmental trade agreements). It is people's response to economic opportunities *mediated by institutional factors* that drives changes [Lambin, 2001 #252].

Modeling is one of the methods in the portfolio of techniques and approaches available to unravel the dynamics of the land use system [Verburg 2006]. There are different types of models in the literature, as reviewed in [Briassoulis 2000; Agarwal 2002; Verburg, Schot, Dijst et al. 2004; Verburg 2006]. Such models can be classified in many different ways, according to their goals and technical approaches. In this work, we analyze how to incorporate land tenure institutional factors in land change models. The specific problem we face is to model land change in the Brazilian Amazonia. The Brazilian government, through a series of territorial planning policies in the last decades, created a mosaic of territory units and heterogeneous institutional contexts that strongly influence the land change dynamic in the region. Figure 1 illustrates the situation in Pará State.

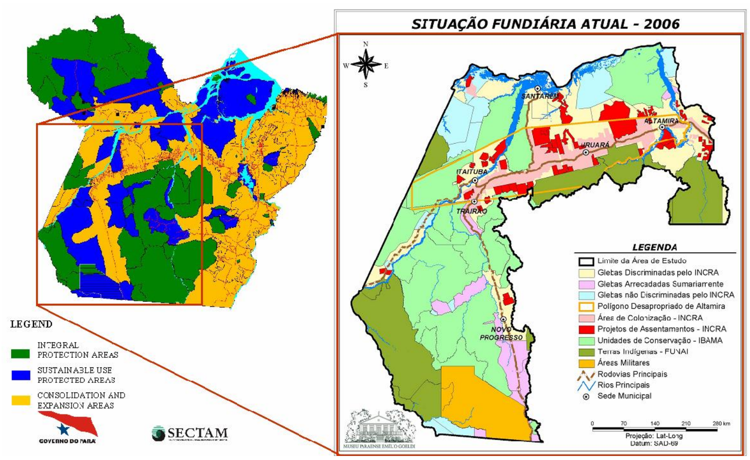

Figure 1. Example of mosaic of territory units in Pará State (sources: Pará State Government and Museu Emilio Goeldi).

These territory units may broadly be characterized into: (a) *Indigenous lands*; (b) Federal and State *Conservation Units* of several types, including the ones oriented towards biodiversity conservation, communitarian exploration resources, and wood exploration use concessions; (c) *Settlement Projects*, also of several categories, including those designated to familiar agriculture and, more recently, to agroextrativism exploration; (d) and, finally, *Expansion Areas*, which consist of all the areas available for expansion of cattle ranching, mechanized and familiar agriculture. Most activities in (d) occur in areas without regular titles of land property. These are, in general, the more conflicting areas in the Amazonia. Most of them still belong to the Federal and State governments, who have the power to discriminate the goal of a given unit. Territory units in categories (a), (b) and (c) have specific rules regarding their destination and land use. For example, in a recently created settlement modality called PDS (Sustainable Development Project), only a small number of families are favored, and their economic activities must be oriented towards forest products exploration. In this settlement modality, each family can clear-cut only 3 ha to subsistence agriculture. On the other hand, in (d), large, medium and small agriculture farmers must respect environmental rules according to the Federal Forest Law, which imposes that 80% of forest inside private properties must be preserved. In all categories, however, rules are often not followed by local actors.

Previous land-change modeling exercises in the region ([Laurance, Cochrane, Bergen et al. 2001; Soares-Filho 2004; Aguiar 2006]) did not explicitly considerer the fact that each of these categories has different actors and rules acting on them. In previous models, the existence of conservation units and indigenous lands slows down - or completely shields - forest conversion from happening. The heterogeneity of types of conversation units and settlement modalities were not considered. However, land changes *do* occur in the different categories, following specific rules regarding allowed actors, land uses and also speed of change. The scientific question we discuss in this paper is *how to incorporate such institutional land tenure categories and their specific rules in land change models.* Our hypothesis is that this is an essential step in the direction of constructing regional models to represent the heterogeneity of actors and processes, which could be used as tools to support public policies. Incorporating the main land tenure categories in regional models will help to make visible the "invisible actors and processes", even when detailed cadastral information about individual properties are not available.

This paper is structured as follows. In Section 2, we present a brief revision about land-change models, focusing on the difference between *Top-down* and *Bottom-up* design approaches. Section 3 discusses conceptually how to incorporate the land tenure aspects in regional models. In Section 4, we describe a computational implementation of these concepts. Section 5 describes one case study in the Brazilian Amazonia, in Santarém, Pará State. Finally, Section 6 presents our conclusions.

2. Land change modeling overview

There is a large diversity of modeling approaches in the literature. In this review, we focus on a classification based on design approach: *Top-down* and *Bottom-up. Top-down* models originate from landscape ecology, and are based on remote sensing and census data. The *Top-down* approach describes a whole study area through of a statistical or mathematical formulation. On other hand, models conceived using a *Bottom-up* approach describe explicitly the actors of land change. They describe individual agents and their interaction with environment, as showed in Figure 2. Next section details and exemplifies both approaches.

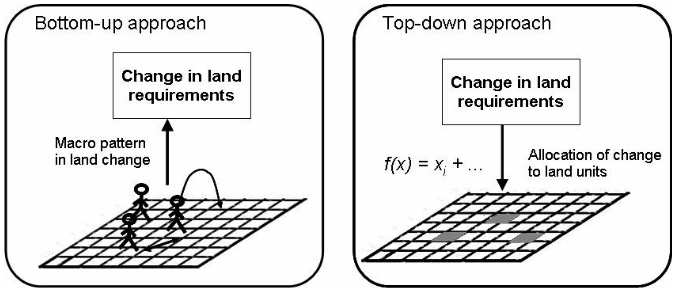

Figure 2. Top-down and bottom-up approaches (adapted from: [Verburg 2006]).

2.1 Top-down approach

Top-down models consider in general land-uses/covers as a set of discrete states. Land changes are transitions from one to another [Walker 2004]. Raster or cellular space, subdivided in pixels or cells represent each discrete state. This approach uses an empirical, mathematical, statistical or econometric equation to describe the transitions among states. There are different models in the literature: CLUE [Veldkamp and Fresco 1996; Verburg, De Koning, Kok et al. 1999], CLUE-s [Verburg, Soepboer, Veldkamp et al. 2002], Dinamica [Soares-Filho, Cerqueira and Pennachin 2002], RIKS [White and Engelen 1997; White and Engelen 2000], CA_Markov [Eastman 2003]. The structures of these models present some likenesses, as discussed in [Eastman, Solórzano and Fossen 2005] or [Verburg, Kok, Pontius et al. 2006]. Eastman [2005] argues that models consist of three major parts: a *change demand submodel, a transition potential submodel, and a change allocation submodel*. The *demand submodel* calculates the rate and magnitude of change, usually based on economic model, trend analysis, or scenario analysis to quantify the change (or demand). This demand is then allocated in a spatially explicit grid by the *change allocation*. This submodel uses a suitability (or change transition potential) maps representing the suitability/or potential for change of each cell for a given land use/or transition. This map is produced by *transition potential submodel*, given a set of input driving factors a method to relation these maps, as a multivariate statistical. The change allocation produces then a new land use map that can be use to next model iteration. In some cases, the rate of change may be modified by the results of the allocation module, in a bottom-up feedback mechanism [Verburg 2006], although this is not always the case. Most models adopt a purely top-down design. Figure 3 illustrates the structure of models using the top-down approach.

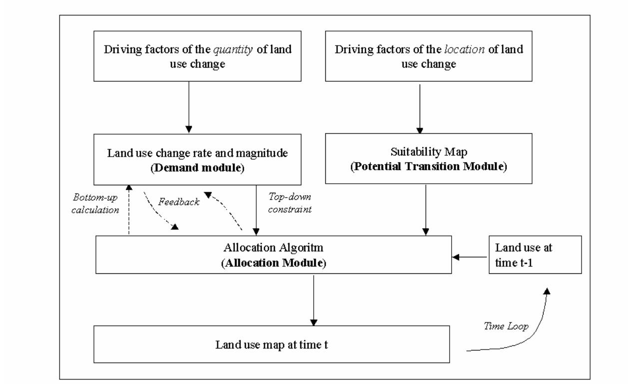

Figure 3 – The generalized model structure of spatially explict land-use change models. Source : [Verburg, Kok, Pontius et al. 2006].

2.2. Bottom-up approach

Bottom-up models are based in the concept of "emergence" that is an essential characteristic of social simulation, where the interactions among each entities at a lower level to result in macro pattern [Matthews, Gilbert, Roach et al. 2005]. General examples include bird-flocking model [Reynolds 1987] and segregation model [Schelling 1971]. In the land change context, this approach includes micro-economic and agent-based approaches. Microeconomic models consider that individual landowners make theirs decisions with the objective to maximize expected returns or utility derived from the land based in economic theory [Verburg, Schot, Dijst et al. 2004]. An agent-based model consists of autonomous entities (agents), an environment where the agents interact (normally represented by a cellular space), and rules that define the relations between agents and their environment [Parker, Berger, Manson et al. 2002]. Figure 4 shows the structure of agent-based models. Each agent can interact with other agents, and can modify the environment and influence other agents.

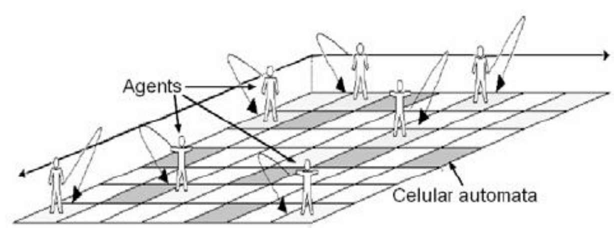

Figure 4. Agent based modeling: Adapted from [Parker, Berger, Manson et al. 2002].

2.3. Which approach is the best?

The use of either a top-down or bottom-up approach depends on the extent of analysis and the dominant processes of land use change in the studied area. The *Top-down* approach is adequate to processes in which the changes are largely steered by regional demand, as in the case of the expansion of cash crop agriculture in regions with abundant land resources [Verburg 2006]. Top-down models are easier and faster to construct than bottom-up models to larger areas. There are a number of available frameworks for top-down modeling (such as CLUE, CLUE-S, DINAMICA), which mostly requires parameterization for the specific case study, including the selection of driving factors, and definitions about how to compute demand and the transition potential. Remote sensing and census data can be use as the main inputs to analyze land use/cover patterns and derive driving factors relations. *Bottom-up* models require extensive fieldwork to design agents' rules and behavior, and are normally constructed for smaller areas, aiming at specific research questions. However, top-down models are derived on pattern analysis, and a series of simplifying assumptions are incorporated. They can't express the heterogeneity of actors and processes as well as Bottom-up/agent-based models ideally could. Bottom-up models have the potential to represent the complex biophysical and socioeconomic process, the interaction of actors at different levels of organization.

The selection of a given approach is very much dependent on the modeling goals. In the current *State of Art* of land change models, it is almost a tradeoff between heterogeneity and scale of analysis. One of the challenges of this scientific field is to combine both approaches, as purely bottom-up or top-down may be insufficient to represent biophysical and socioeconomic processes interactions at different levels of organization, from local to global. A discussion about hybrid approaches can be found in [Verburg 2006] and [Moreira, Costa, Aguiar et al. 2008].

In this paper, we focus mainly on Top-down land change models, as our main goal is the construction of regional scale models. Besides, models constructed using the Bottom-up approach would be naturally able to include such heterogeneity of actors and rules. In the case study presented in Section 5, we analyze how the existence of different rules of territory use affects the landscape dynamics at the regional level. In the next session, we present our conceptual proposal for the inclusion of such heterogeneous land use rules in top-down land-change models.

3. Different territory rules in top-down land change models: conceptual proposal

We analyze two aspects of the heterogeneity of rules in the Brazilian Amazonia in their incorporation in land change top-down models: (1) the temporal evolution of such rules, as different unit are created; (2) allowed uses and conversions in different units. As described in Section 2, Top-down models are composed of three sub-models: Demand, Allocation, Potential Transition. The incorporation of such heterogeneous rules can be achieved by the regionalization of one of these components, or a combination of them. Previous modeling works have done this in different contexts, trying to incorporate some level of heterogeneity in top-down models. In this section, we discuss some of the possibilities:

1. *Regionalize the three components*, creating different models for each unit. A similar approach was used in [Carneiro, Aguiar, Escada et al. 2004] with the goal of creating different models for large and small farmers. In our case, totally different models for each category could be implemented, including different Allocation and Transition Potential rules.
2. *Regionalize only the demand*: keep the same allocation and transition potential modules, but externally compute different speeds of change for each unit. Similar approach was used on Aguiar [2006] and Soares-Filho [2006] to force different rates of change in different regions of the Amazonia.
3. *Keep the three components basically the same*, and regionalize only the parameters for the potential transition module. A similar approach was used in some applications of the CLUE model in large regions such as China [Verburg and Veldkamp 2001].

The choice of a proper solution is a matter of the modeling goal. In the case study we discuss in this paper, our aim is to analyze the landscape dynamics for the whole area of study, considering the implications of the existence - and enforcement - of alternative rules. In this case, option 3 is more appropriated, as we are more interested in the distribution of change over the whole territory, than in actual amount of change. So, to illustrate such concepts, we implemented a top-down approach, with the same demand and allocation module, but using specific rules to compute the transition potential for different use in different categories of land tenure units. Such rules may vary along the time, as new units are created. We choose to adapt an existent top-down model, the CLUES-S [Verburg, Soepboer, Veldkamp et al. 2002]. The same adaptation could be implemented in similar models, like DINAMICA [Soares-Filho, Cerqueira and Pennachin 2002] and CLUE [Veldkamp and Fresco 1996].

4. Implementation

To test the concepts discussed in last section, we implemented a top-down model based on the CLUE-S framework [Verburg, Soepboer, Veldkamp et al. 2002] basic ideas and conceptual design. The new model was implemented using TerraME modeling environment [Carneiro 2006] CLUE-S is a typical top-down hierarchical model. The allocation module uses an externally defined *Demand*, computed using the usual trend analysis, scenario formulation, etc. The *Potential Transition module* computes the cell suitabilities for different uses using logistic regression analysis. Recent applications of the CLUE-S model modified the cell suitability computation to include expert knowledge. Castella and Verburg[2007] for example uses a rule-based version to CLUE-s model. The *Allocation Module* calculates, with discrete time steps, the most likely changes in land use given the suitabilities, and some possible restrictions, which may be informed as parameters to the allocation module:

- Allowed land use transitions in the study area (for instance, forest can be converted to agriculture, but not directly to secondary growth vegetation). These allowed transitions are represented as *Transition Matrices*.
- Spatial policies and restrictions, representing areas in which certain conversions cannot occur (for instance, forest conversion not allowed inside parks);
- Temporal restrictions indicating the minimum and maximum number of years before a conversion can occur. For instance, within a shifting cultivation system, the number of years a piece of land can be used due to soil nutrient depletion and weed infestation.

Another important parameter to the *Allocation module* are *land use elasticities*, which indicate the relative difficulty to modify a certain use (for example, a industrial area can be more difficult to remove and convert to another use than a pasture area).

The model we implemented is inspired and based on the concepts of the CLUE-s model as presented by [Verburg, Soepboer, Veldkamp et al. 2002]. The main difference relies in the possibility to extend the above-mentioned spatial restrictions regarding allowed conversions to allow multiple regions/transition matrices. In this paper, each region represents, a different type of territory unit, with their specific rules, as discussed in Section 1. In other applications, other types of regions could be emplyed. Another difference from the original CLUE-S resides in the fact that other parameters (land use elasticities and driving factors) can also be regionalized. The regionalization may evolve with time, as new territory units are created, through a *Regionalization Module*. Figure 5 illustrated these modifications. At each time step, the *Regionalization module* updates an attribute of each cell corresponding to the type of region it belongs. This attribute is used in the Allocation module to select the appropriate parameters (possible transitions represented as alternative Transition Matrices; Land Use Elasticities; and Driving factors) to compute the *Transition Potential* of each cell.

On the other hand, in comparison to the original CLUE-S model, our model does not include the temporal restrictions on the conversions (minimum and maximum number of years before a conversion can occur), nor recently added functionalities of the CLUE-S model, such as cellular automata /neighborhood functionalities.

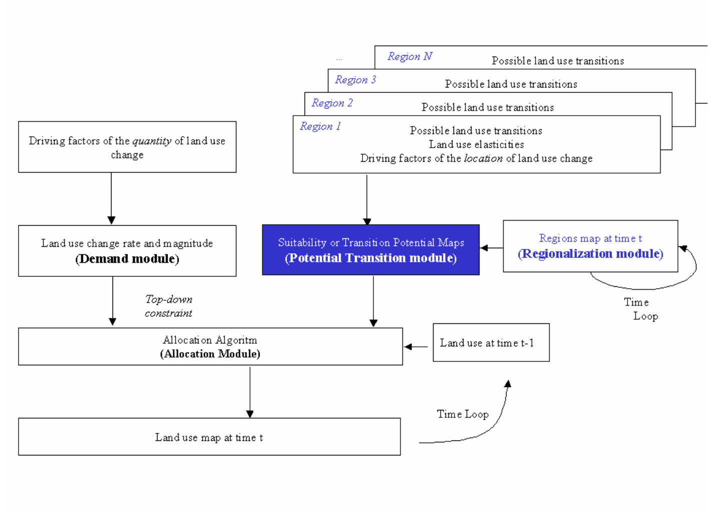

Figure 5. Modified top-down model to include regionalization.

5. Case Study

The goal of the modeling exercise we present here in to test the inclusion of the institutional land tenure factors in a real-world case study. We selected the Santarém region land use dynamics from 1999 to 2007. We compare the use of heterogeneous and homogeneous rules over the landscape, in order to analyze adherence of the official rules of use of the territory to the real patterns identified in the multi-temporal image classification, as described below.

5.1 Study area

The Santarém region, in Pará State, presented an intense land change dynamics due to the expansion of mechanized agriculture in the last decade, in substitution to familiar agriculture, secondary forest and forest areas. Figure 6 illustrates the study area. It comprehends part of the Santarém, Belterra and Placas municipalities.

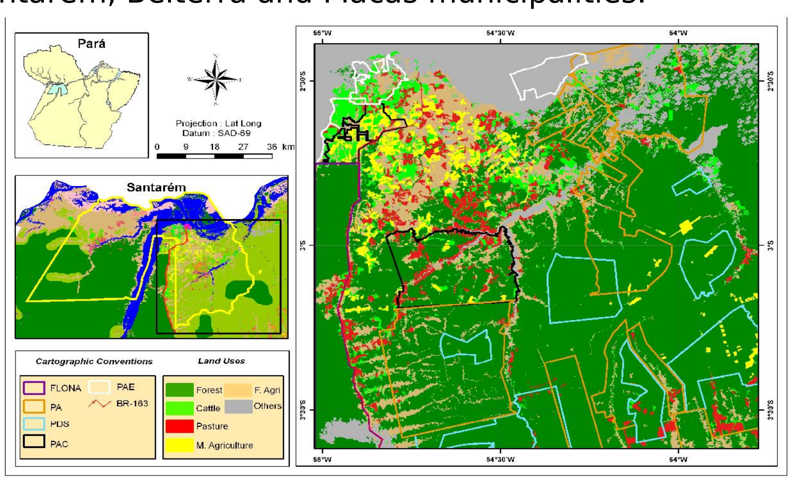

Figure 6 – Study Area (source: Andrea Coelho, IDESP).

As illustrated in Figure 6, this area encompasses a mosaic of different territory units, including a Conservation Unit, the Tapajós National Forest. A National Forest (FLONA) is a type of conservation unit that allows sustainable economic activities, according to a management plan for forest resources exploration. Existing population is allowed to stay when FLONAS are created, and practice subsistence agriculture. The study area also include 27 Settlements of four different modalities:

- 10 PA (*Projeto de Assentamento*), designed to familiar agriculture, for purposes of colonization and homestead. It the traditional type of settlement created after the 80ths. Each family has less than 100 ha, which can be used to diverse agricultural activities, respecting the Federal Forest Law.
- 3 PAC (Projeto de Consolidação de Assentamentos): this modality was created to regularize the situation of already installed farms. Land property is collective.
- 4 PAE (Projeto de Assentamento Agro-extrativista), designed to traditional population, which should base their economy on extractive activities or agriculture. The property title is collective, and the use of natural resources has to be decided in a communitarian manner.
- 10 PDS (*Projeto de Desenvolvimento Sustentável*), designed to low environmental impact activities based on forest products. Each family is allowed to use only 3 ha to subsistence farming. Title is also collective.

FLONA Tapajós was created in 1974. The PA's in the study area were created after 1995. All the other units were recently created, after 2005. The official rules are not followed in many cases. As Figure 6 illustrates, in 2007 there is mechanized agriculture, which is associated to capitalized actors, inside PDS and PAC areas.

5.2. Spatio-temporal database

The first step of model construction is the creation of a spatio-temporal database for the study area. The database contains information about the land use dynamics and potential determining factors aggregated in regular cells of 500 x 500 m^2, representing thee different dates: 1999, 2004 and 2007. The model considers five land use classes: *forest, secondary growth, cattle ranching, familiar agriculture, and mechanized agriculture*. They were obtained though classification of Landsat TM images. Cells representing water, cloud, and non-classified pixels were discarded from analysis. Driving factors of location of change include: distance to roads, to rivers, to urban centers, slope, and soils quality. The database also includes information about the different territorial units in the area. Each cell is classified according to the type, year of creation of the existing units in a given year.

5.3. Different transition rules according to institutional aspects

The relative importance of the driving factors was established using logistic regression analysis for each land use. These coefficients are used to compute cell suitabilities in the Transition Potential Module. These coefficients were adapted using field experience and expert knowledge, during a calibration phase. Elasticity factors were also determined during a model calibration phase, comparing model results to 2004 real patterns. In the results we show in this paper, we opted for maintaining the same driving factors, their suitability computation coefficients, and elasticity values for all types of units. The heterogeneity is translated into alternative Transition Matrices representing allowed land use conversion in each of the five types of units present in the study area: FLONA, PA, PAE, PDS, PAC and Expansion Areas. Table 1 illustrates such matrices.

Table 1. Examples of Transition Matreices for PAC and Expansion Areas

PAC allowed Transitions	Forest	Secondary Vegetaion	Cattle ranching	Mechanized Agriculture	Familiar Agriculture
Forest	1	0	0	0	1
Secondary Vegetaion	0	1	0	0	1
Cattle ranching	0	0	1	0	0
Mechanized Agriculture	0	0	0	1	0
Familiar Agriculture	0	X	0	0	1
Expansion Area Transitions	Forest	Secondary Vegetaion	Cattle ranching	Mechanized Agriculture	Familiar Agriculture
Forest	1	0	1	1	1
Secondary Vegetaion	0	1	1	1	1
Cattle ranching	0	1	1	1	1
Mechanized Agriculture	0	1	1	1	1
Familiar Agriculture	0	1	1	1	1

5.4. Exploration of alternative rules

In order to analyze the adherence of the official rules of use of the territory to the real land-use patterns dynamics in the period 1999-2004-2007, we compare the results of two alternative model simulations:

A. Using heterogeneous rules for each class of special area

B. Using a homogeneous rule, the same valid for the agriculture expansion area

Notice that the goal here is not to obtain the exact patterns (i.e., to achieve a high level of correctness in the classification), but to use the model as an additional tool to understand in which situations the rules are not being following, and to capture how the overall landscape dynamics is influenced by the mosaic of uses and special areas that compose the area. The demand for change (amount of change per land use) is obtained from the 2004 and 2007 maps, and interpolated for the intermediary years.

5.5. Simulation results in a PAC area

In this section, we illustrate some of the results obtained in the modeling process using the approach presented in this paper. We focus on a specific area in which rules are not being followed in a PAC area (Figure 7).

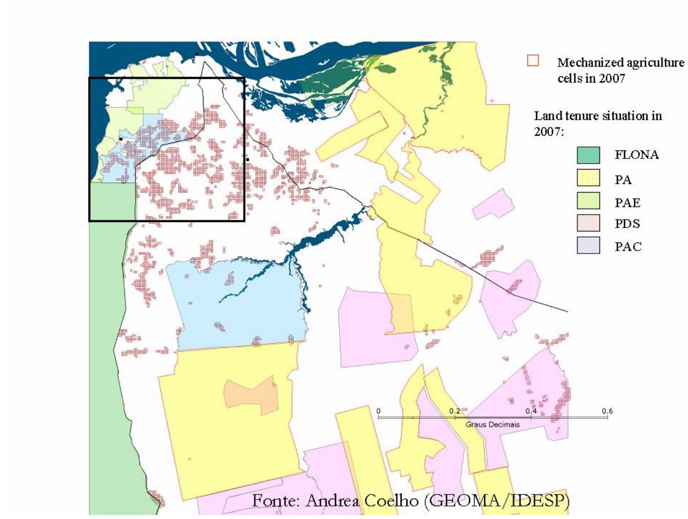

Figure 7– Selected area to analyze the territory rules enforcement in the land change model.

Figure 8.a and 8.b illustrate the real land change occurred in the area. Figures 8.c and 8.d compares two alternative results: considering or not the heterogeneous rules of territory use.

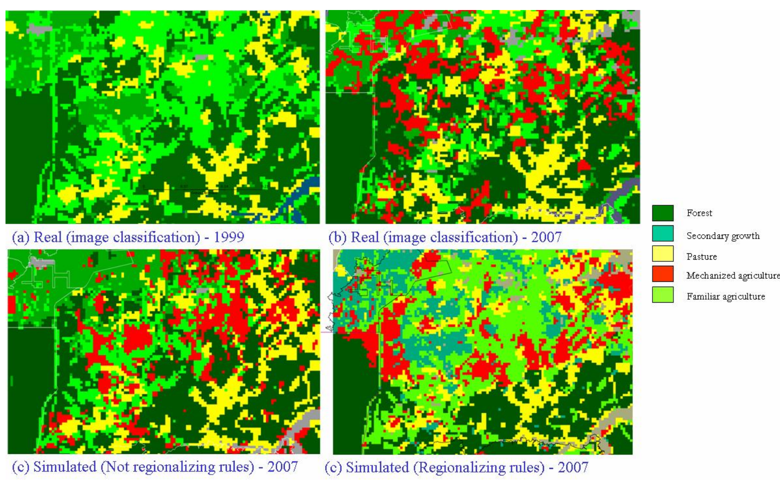

Figure 8– Results comparing PAC area: (a) Land use map in 1999; (b) Land use map in 2007; (c) Simulated results (2007) without regionalization; (d) Simulated results (2007) with regionalization.

As Figure 8.b illustrates, the PAC area is dominated by mechanized agriculture in 2007. Using the non-regionalized model, some of this process is captured in the simulated result (Figure 8.c). On the other hand, when the correct rule is applied to the PAC (Figure 8.d), a totally diverse result is obtained. The only allowed use, according to Table 1, is familiar agriculture.

6. Conclusion

In this paper, we discussed how to incorporate land tenure institutional land tenure categories and their specific rules in top-down land change models. We implemented a model to test our proposal in a agriculture expansion frontier in Central Amazonia. We conclude that the whole modeling process gets richer and insightful when such institutional aspects are considered. Land tenure information provides information about what we can (and can't) see in remote sensing derived information. Incorporating such information in regional models will help to make visible the "invisible actors and processes", even when detailed cadastral information about individual properties are not available.

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