Assessing risk maps of deforestation to the Brazilian Amazon using LuccME framework

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Abstract. Currently Amazon land use/cover changes are closely related to its impact on regional policies. These policies can be based on deforestation data resulting from land cover models, which may be based on on empirical analysis of potential factors determining its patterns and processes. However, when only data from total deforestation are shown, it can cause misinterpretation of the recently cleared areas, inducing poor decision-making. In the present study were constructed deforestation risk maps of Brazilian Amazon from the simulations results obtained by a regional scale model for the Brazilian Amazon called LuccME / BRAmazonia. This model was built using a modeling framework developed by CCST / INPE, which allows to build integrated models that combine different modules of demand, transition potential and land use/cover changes allocation. We made simulations with two different demand scenarios (Baseline and carbon Emission Reduction Target scenario) for 2020, and the second one was chosen to create the risk map. This map represents the difference between foreseen deforestation in 2020 and actual deforestation in 2006. Thus, it was possible to find most susceptible areas to deforestation in coming years.

Keywords: deforestation, empirical analysis, land cover and land use change, risk assessment.

1. Introduction

In recent years, the importance of land use and land cover change models in the Brazilian Amazon has been strongly connected their impact on governance at the regional level (Laurance, 2001; Câmara et al. 2005). Detailed studies in the region have indicated that spatial heterogeneity of deforestation can be reasonably captured by land cover change models based on empirical analysis of potential factors determining its patterns and processes (Aguiar et al., 2007; Soares-Filho et al., 2006, Soler et al, 2009). Despite their inherent limitation in capturing non-linear changes, not only spatially explicit models in the region have become relevant to support land occupation planning, but also governmental decision regarding greenhouse gases emissions from deforestation and agricultural expansion (Brasil, 2008; INPE, 2009).

In this context, recent concerns regarding the maintenance of environmental services, greenhouse gases emission and REED initiatives can benefit from coherent and trustful methods to assess risk maps of deforestation based on land cover change models. However, the interpretation of direct outputs from land cover change models might cause erroneous interpretation of recently deforested areas, especially in models for large areas and sparse data such as the Brazilian Amazon. This limitation indicates the need of developing appropriate methods to represent the outputs of land use and land cover change models in a straightforward way to facilitate decision making at several levels of organization. Therefore, as part of a collaborative project between the Brazilian National Institute for Space Research and Planetary Skin Institute founded by CISCO, the present study aims to assess risk maps of deforestation in the Brazilian Amazon using a deforestation model framework developed in the Earth System Centre (CCST/INPE).

2. Study area

The colonization process in the Brazilian Amazon began in the XVIII century during the first rubber cycle, but was intensified only in the late 1960's when the federal government built several roads connecting existing urban areas such as Manaus, Belém and Porto Velho to the recently created State capital Brasília (Teixeira & Fonseca, 2000). These infrastructural changes intensified the colonization process especially because of governmental investments and fiscal incentives to encourage migration from farmers of South and Central parts of Brazil. These strategies intended to establish an occupation process at threatened political boundaries and to integrate the remote regions to the capital Brasília (Becker, 1997, 2004; Machado, 1998). As a result, INCRA created many colonization projects and opened vicinal roads to connect the lots to urban areas. Between 1960 and 1980 the population growth of region was 16% per year (Perz, 2002) and the total population increased from 70 to 500 thousand (IBGE, 1981). Beyond subsistence or small scale commercial agriculture and cattle raising activities mineral exploitation was also encouraged by the government.

Historical census data show that planted pasture is the predominant land cover in the region, but recent surveys and remote sensing analysis indicate an increase in annual crops, especially in Mato Grosso State, which seems to be linked to the agrarian structure on this State predominantly of large farmers (IBGE, 1996, 2006; Morton et al., 2006, Barona et al. 2010). In addition, regional case studies revealed that deforestation in some area have been driven by timber exploitation (Matricardi et al. 2007, Arima et al. 2008).

Even though changes in the spatial distribution of land use/cover types in the Brazilian Amazon are linked to socioeconomic to infrastructural factors (Browder et al. 2004; Soler et al., 2009), one must consider that the spatial heterogeneity of occupation patterns results in anisotropic causality of factors in different parts of the Brazilian Amazon (Aguiar et al. 2007; Becker, 2004). This spatial heterogeneity of the region can be partially captured by environmental aspects, such as soil fertility, slope, rainfall regime and temperature (Nobre et al., 1991; Chomitz & Thomas, 2003; Sombroek, 2001). Therefore, when dealing with land cover change models, one must take into account the enormous variety and the spatial heterogeneity of potential factors influencing deforestation. In the present study we attempted to capture this heterogeneity by assembling a comprehensive database of potential factors retrieved from distinct data sources at similar scale of analysis. Further details are given in the next sections.

3. LuccME framework

LuccME is a framework developed at INPE and built on top of TerraME, a general programming environment for spatial dynamical modeling designed to support models in several domains, including land use systems, hydrology, biodiversity, urban studies and many others. Its programming language interface has in-built functions that make it easier to develop multi-scale and multi-paradigm models for environmental applications (Carneiro 2006, Carneiro et al. 2004).

LuccME framework allows the construction of integrated models that can be taken from existing literature or from yet experimental modeling approaches. LuccME framework is able to combine elements from previously defined modules of demand, transitional potential of change and land use/cover change allocation. Once inside LuccME, these modules can be easily parameterized through a simple user interface, according to the requirements of particular geographic regions and scales of analyses. A specific parameterization setting configures then a specific model inside LuccME.

In this study we created a specific model at the regional scale inside LuccME for the Brazilian Amazonia called LuccME/BRAmazonia. This model uses transitional potential and allocation sub-modules based on the CLUE model (Veldkamp and Fresco, 1996; Verburg et al., 1999; Verburg et al., 2002), adapt to the Amazonia by Aguiar (2006). The model LuccME/BRAmazonia uses a spatial database organized in a regular grid of 25x25 km^2, where land use classes are represented in percentage of forest and deforested areas in each cell. In order to calculate the transitional potential sub-module, LuccME/BRAmazonia takes into account potential factors of deforestation including market connectivity, agrarian structure, socio-economic, environmental, public policy and technological aspects. These potential factors are translated into specific variables used to estimate empirical linear regression models of forest and deforested areas, which are the basis to calculate the transitional potential sub-module. Demand sub-module is calculated externally and depended upon the scenario of change adopted.

4. Data and methods

This section describes the database and the methodological steps adopted to assess the risk maps of deforestation in the Brazilian Amazon based on two specific scenarios of land cover change tested in a dynamic empirical model developed inside LuccME framework.

4.1 Spatial database

In order to run LuccME/BRAmazonia model, a spatial database containing land cover maps from the PRODES project and potential factors of land cover change were adopted and comprise technological attractiveness (wood poles and mining areas), accessibility measures, environmental aspects, agrarian structure and public policies of land occupation. Based on the literature cited here, these factors were expected to capture most of the spatial heterogeneity of deforestation patterns. The potential factors were codified into 35 variables which were included in the exploratory analysis that represented the first of the empirical analysis to estimate linear regression models.

4.2 Linear regression models

The exploratory analysis aimed to select the most relevant variables from the universe of 35, as mentioned before, using 2006 as the baseline year. By analyzing the Pearson correlation matrix, it was possible to identify variables highly correlated to each other, and the select the one most correlated to deforested patterns. Correlation coefficients higher that 0.6 were not used together in the same regression model. The initial exploratory regression models were tested using the variables presenting the highest correlation to deforested areas and considering previous results of studies cited in this paper.

Several alternative models were tested by including or excluding some variables depending on their individual significance in model estimates. The final model was the one that maximized the R square at a minimum of 0.7 and at the same time presented high significance for the model as whole as for the individual variables (5 % significance level). Stepwise variables selection method was also used to improve the models together with graphical analysis of normal p-plots and residual analysis. The final linear regression model included the variables listed in Table 1.

Table 1. Variables adopted in the linear regression model of deforestation, with indicated scale and source of data.

Variables Description	Source
% cumulative deforested area	PRODES, 2006 (www.inpe.br/prodes)
% remaining area of forest inside cells	
Distance to paved and unpaved highways	IBGE, 2006
Distance to paved highways	
Distance to unpaved highways	
Distance to main and secondary rivers	
Distance to main rivers	
Distance to urban centers in the Brazilian Amazon	
Distance to main ports (with national and international commerce)	
Distance to São Paulo	
Distance to main urban areas (all Brazilian state capitals)	
Connection to market in São Paulo	IBGE, 2006 Aguiar et al., 2003
Connection to market in São Paulo and Rio de Janeiro	
Connection to market in São Paulo and the Brazilian Northeast	
Connection to ports	
Connection to state capitals in Brazil	
Connection to municipalities seats (main urban areas) in the Brazilian Amazon	
Distance to mineral reserves (under exploitation and/or economic relevant)	CPRM, 2006
Distance to wood extraction poles (sawmills, wood forest management areas)	MMA, 2006
Official agrarian projects under land concession regimes allowing only sustainable exploration	
Official agrarian projects under land concession regimes allowing slash and burn practices	
Slope: Steep (>20%), Moderate (between 11 and 20%), Smooth (between 5 and 10%), Flat (up to 5%)	SRTM (NASA, 2000) refined to 30 m by TOPODATA project (VALERIANO, 2007)
Soil fertility: High, Low, Very Low	IBGE 1996/EMBRAPA 2000
Climatic factors: Average precipitation given by the minimum value per pixel within 3 consecutive months, Average humidity given by the minimum value per pixel within 3 consecutive months, Average temperature given by the minimum value per pixel within 3 consecutive months	INPE/CPTEC
PVM-CPTEC climatic-vegetation model	
the mean temperature of the coldest month	Derived from the water balance model consisting of a submodel of CPTEC-PVM described in Oyama & Nobre, 2004
the number of growing degree days using a 0°C threshold	
the number of growing degree days using a 5°C threshold	
wetness index indicating the potential of the areas of higher humidity	
Indigenous land existing in 2006	MMA, 2006
Protected areas under different levels of law enforcement: Existing in 2006, Existing in 2007, Existing in 2008, Existing in 2009	

4.3 Simulation procedure and the scenarios adopted

LuccME/BRAmazonia model performs several iterations for each year of the simulation in order to allocate the informed demand values of forest losses. The baseline year is 2006, following the same of regression models. Once the demand is allocated, a projected land use map is recorded and then used to start the next time step of the simulation. The allocation procedure is based on the results of the regression model, which procedure was described in the previous section. In addition to allocation of changes and demand scenarios, LuccME/BRAmazonia model requires expert knowledge also to set specific model parameters concerning spatial variability and reversibility of changes. Specific parameters of reversibility distribute the demand in such a way that deforestation can not be easily allocated in cells already highly deforested and set a maximum limit in which a cell can be deforested. Both parameters can be chosen by the user.

Simulations using LuccME/BRAmazonia model were performed using 2006 as the starting year and 2020 as the end year. Two deforestation scenarios were adopted being the first one based on the historical deforestation in Amazon (baseline scenario) and the second based on carbon emission reduction target, proposed by the Brazilian government (Brasil, 2008).

In 2008 the Brazilian Government made a formal announcement under the United Nations climate treaty framework of reducing Amazon deforestation by 80% compared to the historical rate from 1996-2005 of 19500 km^2 yr^{-1} by 2020 (Brazil 2008). According to the target, deforestation rate would drop to 3900 km^2 in 2020. This target is in full-association with the voluntary commitment assumed later on December, 2009 by Brazil in the United Nations Climate Change Conference in Copenhagen to reduce its greenhouse gas emissions from 36.1% to 38.9% by 2020.

Therefore, in the baseline scenario we consider the historical rate of 19500 km^2 yr^{-1} from 2010 to 2020. In the carbon emission reduction target scenario we assume that deforestation rates will decrease exponentially from 2010 to 2020, when it would reach 3900km^2, following the Brazilian governmental policies to mitigate greenhouse gases emissions. In both scenarios we used the PRODES increments from 2006 to 2009.

4.4 Assessing risk maps

The calculation of the risk assessment map of deforestation considers the same spatial scale and spatial resolution of LuccME/BRAmazonia. To obtain this map we calculated the difference of deforested areas between 2020 and 2006 that results in a transitional potential between 0 and 1 for each cell in the database to be deforested within this period. Therefore the map of risk assessment of deforestation can be interpreted as the risk of deforestation in the forthcoming years based on the scenario of carbon emission reduction target.

5. Results and Discussions

In order to analyze the results obtained by LuccME/BRAmazonia model we compared the simulated land cover map for 2009 over the land cover map from the PRODES project for 2009. The model reproduced the deforestation dynamic in a satisfactory way, especially along the Densely Populated Arch according to Bertha (2004) nomenclature. Satisfactory results were obtained especially in the north of Mato Grosso, where annual crops have been partially responsible for recent deforestation rates, as well as along the Amazon River and in recent hot spots in Amazonas and Acre. This behavior can be observed in Figure 1. Some regions such as the Sustainable Forestry District of BR163 and along BR319 did not present satisfactory results, which can be attributed mainly to the spatial resolution adopted once these hot spots are also affected in the PRODES data. Despite that, the overall pattern of deforestation in the region as a whole was captured by the model, which gives credit to the land cover change projections based on scenarios presented above.

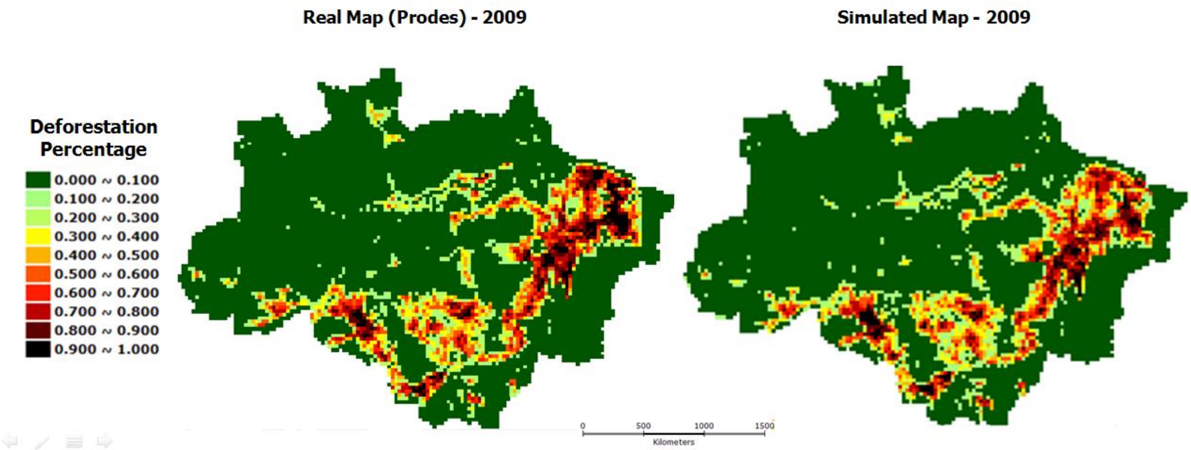

Figure 1. Comparison between the PRODES land cover map from 2009 and the simulated result using LuccME/BRAmazonia.

The simulations results for 2020 are represented in figure 2 that illustrates the land cover change projects using the proposed scenarios. The baseline scenario clearly shows intensification of deforestation in previously deforested areas, but better illustrates the new frontiers in Acre, Amazonas and BR-163. In the *carbon emission reduction target scenario* the political pressures are well represented as the intensification of deforestation is smaller. However, the recent hot spots of deforestation were poorly captured. Despite that, we consider this scenario the one that better fits to the real current situation considering the constant decrease in deforestation rates since 2007. Considering that, this scenario was chosen to be the baseline to calculate the map of risk assessment of deforestation.

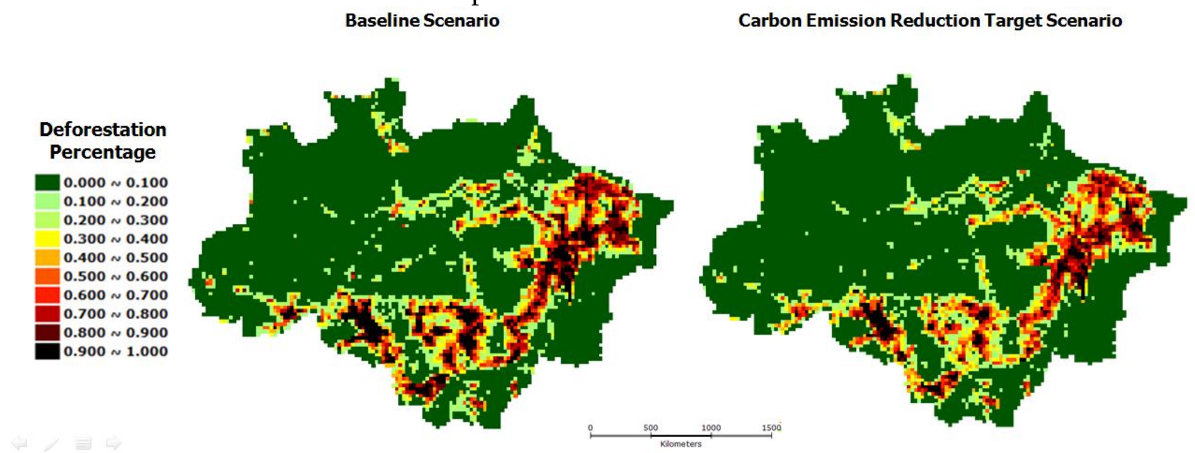

Figure 2. Scenarios for 2020: baseline and carbon emission reduction target.

The overall results of the risk map of deforestation can be said to be satisfactory, considering the qualitative comparison between simulated and ground truth results. Because the risk map is based on simulation results, it had better results in areas where the model was best fitted, such as Mato Grosso and Acre States. Most areas with recent deforestation frontiers appear with higher risk than previuously deforestated areas, resulting in a map where the cumulative deforestation does not influence much the visual interpretation of hot spots of deforestation. The areas where cumulative deforestation in moderate (~ between and 50 and 80%) tend to appear within cells of moderate risk. Thus, even though the final user do not have information about a specif region in the Brazilian Amazon, the risk map will not be maximized by more accessible and fertile areas only for example, but also taking into account the land use history embedded in the data adopted for the regression analysis. It should be mentioned that some cells bordering the cell space in the north portion of the study area, presented erroneous high risk indexes due to a border effect of independent variables, which shall be revised for further more conclusive results.

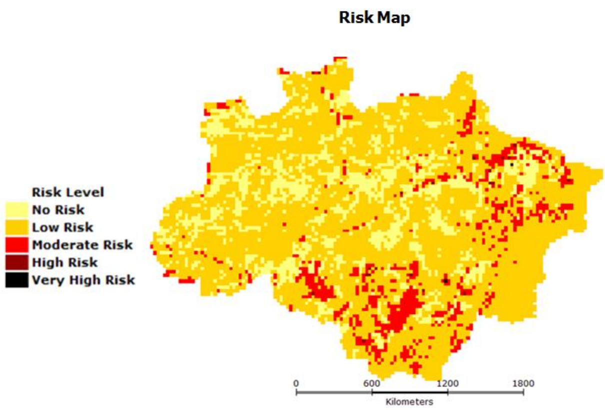

Figure 3. Risk assessment map of deforestation based on the carbon emission reduction target scenario.

6. Conclusions

LuccME framework allows the construction of integrated models enabling to combine elements from previously defined modules of demand, transitional potential of change and land use/cover change allocation. Therefore, LuccME framework provides considerable flexibility in *top-down* models, besides being easy of parameterization and use.

The results obtained by the simulations were satisfactory especially along the Densely Populated Arch (mainly in north of Mato Grosso), along Amazon River and in hot spots located in Amazonas and Acre States. However improvements must be performed to achieve a better goodness-of-fit to the LuccME/BRAmazonia model. Suggestions on that issue are the inclusion of up-to-date socioeconomic variables released by IBGE and the use of a more appropriate spatial resolution (5 km^2). In addition, we suggest better elaborated scenarios regarding combined determinants of economic development and environmental conservation focused on REDD initiatives as example.

The most important contribution of this paper is to propose a trustful method to assess the risk map of deforestation, which brings a more straightforward interpretation of newly deforested areas that are keys to the carbon emission models and governmental targets. At last, we conclude that LuccME framework is a powerful tool that combining demand, transitional potential of change and allocation of change can provide satisfactory results. These results can then be translated into risk maps that help decision makers as well as environmental studies, without requiring prior knowledge of the history of deforestation.

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