Modelling Tropical Deforestation: A Comparison of Approaches

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Abstract – Tropical deforestation, as an important factor in global change, is a topic that recently has received considerable attention. GIS-based spatially explicit models that intend to predict the location of land use/cover change (LUCC) can help scientists and policy makers to understand, anticipate and possibly prevent the adverse effects of land-use change. There are many approaches and softwares to model LUCC such as CLUE-S, DINAMICA GEOMOD and IDRISI. This study intends to compare these four modelling approaches. First, a review of methods and tools employed by each software to carry out the simulation was done. Then, the four packages were applied to a "virtual" case which involves a map of deforestation, which comprises two types of deforestation (forest to shifting agriculture and forest to pasture lands), along with several explanatory variables (drivers). Deforestation was modelled using the four approaches and the output maps were compared.

Keywords: Deforestation modelling, GIS, software programs.

1. INTRODUCTION

Land use/cover changes (LUCC) are significant to a range of issues central to the study of global environmental change. Over the last decades, a variety of models of LUCC have been developed to predict the location of land use/cover change. Modelling, especially if done in a spatially explicit, is an important technique for helping scientists and policy makers to understand, anticipate and possibly prevent the adverse effects of land-use change, by focusing policies on those locations that are most threatened and by developing different future scenarios.
This study aims at evaluating four models developed for the spatially explicit simulation of land use/cover change which have been frequently cited in the literature.

2. MATERIALS AND METHODS

2.1 Models involved in the comparison

We compared four models:

- CA_MARKOV´s IDRISI is a combined cellular automata / Markov change model that adds an element of spatial continuity as well as knowledge of the likely spatial distribution of transition to Markov change analysis. A detailed application of this approach can be found in Paegelow and Camacho (2005).
- CLUE-S (Conversion of Land Use and Its Effects at Small regional extent) is based upon an empirical analysis of location suitability combined with the dynamic simulation of competition and interactions between the spatial and temporal dynamics of land use systems. More information on the development of this model can be found in Verburg et al. (2002).
- DINAMICA (version 2.4) simulates landscape dynamics, using a cellular automata approach to reproduce the way its spatial patterns evolve. DINAMICA has been applied to a variety of studies, including modeling urban growth and dynamics (Almeida et al., 2003) and tropical deforestation from local to basin-wide scales (Soares-Filho et al., 2002, 2006).
- GEOMOD (also available in IDRISI) is a change model that predicts the location of cells which vary between only two change categories (e.g. "forest" to "no forest"). This model has been used frequently to analyse baseline scenario of deforestation (Hall et al., 2003, Pontius et al. 2001). A complete description of GEOMOD can be found in Pontius et al. (2001).

A review of the methods and tools offered by each model to perform the simulation was carried out taking into account the principal tasks involved in spatial modelling: 1) How the model estimates the amount of changes? 2) How it allocates the changes? 3) How it simulate spatial patterns of changes? 4) How the model is validated? We assess also the possibilities offered by each model to perform complex simulations as well as the cost and the availability of manuals, tutorials and helpful material which facilitates the use of the model.

As a following step, each model was applied to a "virtual" case, that is a set of data created by the authors for the purpose of the comparison and including two land cover maps (date 1 and 2) and four explanatory maps (elevation, slope, distance to roads and distance to settlements).

Three different land cover categories were distinguished for the simulation: 1) forest, 2) pasture land and 3) shifting agriculture. During the t_1- t_2 period deforestation presented different patterns. Patches of pasture are larger than patches of agriculture and are created through the expansion of previous patches. Pasture lands and agriculture are associated to gentle slopes and to the proximity of roads and to settlements respectively but these two latter variables are strongly correlated. Finally the effect of several variables is not the sum of the effects of each variable. For instance deforestation takes place in locations with gentle slope and close to roads or settlements.

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3. RESULTS

3.1 Review of the models

The simulation procedure of these models can be sub-divided into two or three steps, 1) a non spatial procedure which calculates the amount of each type of change and, 2) a spatial procedure which allocates changes at the more likely locations and eventually replicate the patterns of the landscape and finally, 3) a validation which allows to compare the simulated map with the true map of the same date. The methods and tools offered by each model to accomplish each one of these tasks were reviewed.

Amount of change estimate

In CLUE and GEOMOD, the amount of each type of change are provided by the user and are usually derived from simple trend extrapolations but eventually can be obtained from complex models such as economic models. In GEOMOD only a binary change can be managed such as "deforestation/no deforestation" and users have to provide an estimate of the number of cells of each of the two categories at the ending time. In DINAMICA and IDRISI (CA_MARKOV module), the changes are computed from a Markov matrix generally obtained through the comparison of land use/cover map of two dates. In DINAMICA, a dynamic matrix, coupled with a non spatial model, can be integrated into the modelling procedure. In CA_Markov and DINAMICA temporal dynamics are directly derived from the markov matrix. Additionally, DINAMICA allows managing a sojourn time (time a land cover should remain the same before it can change to another land cover type). In CLUE, temporal dynamics is controlled by a value of "elasticity" related to the reversibility of change and by a conversion matrices which indicate possible and impossible conversions and sojourn times.

Allocation of change

Land use/cover changes are expected to take place at locations with the highest susceptibility to be converted to a specific type of land use/cover. The susceptibility depends upon biophysical or socio-economical characteristics of the location. In CLUE, GEOMOD and IDRISI, maps of suitability (which express the suitability of a location for each of the land use/cover type under consideration), are elaborated by different methods using explanatory variables (drivers) which are most commonly variables that describe the demography, soil, geomorphology, climate and infrastructural situation. IDRISI allows elaborating such map using different methods (e.g. multi-criteria evaluation, logistic regression, neural networks…). CLUE uses a logistic regression (which should be run in a statistical program) and GEOMOD creates the suitability map by computing a weighted average of the reclassified explanatory maps. DINAMICA calculates a probability map of each type of change using the weights of evidence method. This software presents several tools to define the best ranges employed to categorize continuous variables, evaluate the correlation between pair of explanatory maps and edit, and eventually modify, the weights of evidence.

Reproduction of spatial patterns

CLUE does not offer any method to improve the realism of simulated landscape by reproducing the spatial patterns. Pixels with the higher probability of changes (depending on suitability and facility of conversion of the initial category) are selected by an iterative threshold procedure which allows obtaining the amount of change set by the user. In order to simulate the way in which changed areas grow out of previous change, GEOMOD restricts change to cells that are on the edge between changed and non-changed areas using a square window which size is set by the user. DINAMICA and IDRISI use a cellular automata approach in order to obtain a proximity effect (areas which are close to existing areas of a certain class are more likely to change to this class). A cellular automaton is able to vary its state based on its previous state and of its neighbours according to a specific rule. Whereas IDRISI offers few options to control the automaton (number of iterations, type and size of the filter), DINAMICA allows producing various spatial patterns taking into account, for each transition type, a large number of parameters such as mean patch size, patch size variance, and isometry. Increasing patch size leads to model a less fragmented landscape, increasing patch size variance to a more diverse landscape, and setting isometry greater than one to the creation of more isometric patches.

DINAMICA uses two complementary transition functions: 1) the Expander and 2) the Patcher. The first process is dedicated only to the expansion or contraction of previous patches of a certain class. The second process is designed to generate new patches through a seeding mechanism. The combination of DINAMICA's transition function presents numerous possibilities with respect to the generation of spatial patterns of change.

Validation

IDRISI offers two ways of assessing the simulation results: 1) A modified Kappa agreement index (Pontius, 2000) and 2) the ROC (Relative Operating Characteristics). CLUE model is usually assessed by the ROC method. DINAMICA validation is based upon the fuzzy similarity which takes into account the fuzziness of location and category within a cell neighbourhood (Hagen, 2003).

Advanced simulations

The elaboration of complex model involves splitting the study areas into various sub-regions which can present different dynamics (e.g. different rates of change, different types of transition, different explanatory variables or/and different effect of the same variables). This can be obtained running independent models for each sub-region and, as a following step, mosaiquing the simulated maps. For example, in GEOMOD the user can use a map of regions and specify the quantity of each category at the ending time for each region. In CLUE the user can provide a map of regions associated with their possible conversion. DINAMICA is able to run sub-regional models which can interact (e.g. the proximity of a deforestation front in one sub-region can influence deforestation in neighbour sub-regions) but only in the command line version. Another aspect is the use of different patterns of change during time. This can be easily done with DINAMICA which allows the use of different matrices of transition during simulation iterations. IDRISI´s macro modeller can be used to carry out such modelling procedures using CA_Markov or GEOMOD.

In order to replicate various spatial patterns of Amazonian colonization, e.g. the classical 'fishbone' colonization structure, or the 'organic' type, in which the road network follows the watershed boundaries, a road constructor was developed in the DINAMICA. A similar tool is also available in the last version of IDRISI (Andes version).

Cost, versatility and availability of documentation
All the examined software are free of charge except IDRISI which is a low cost software (US $ 1250 and 675 for a general and an academic license respectively). However, IDRISI is a sophisticated GIS and Image Processing software, leader in cutting-edge classifier approaches which can be used in many other tasks than LUCC modelling. On the contrary, CLUE-S needs other software to display the simulated images and to carry out the logistic regression. With regards to manuals and tutorial, IDRISI presents the more complete set of documentation. Introductory document to modelling with GEOMOD and CLUE-S are available. In the case of DINAMICA, a manual is lacking but the package has a wizard which is helpful to carry out the modelling procedure.

3.2 Application to the virtual case

The four packages were applied to the virtual LUCC case (figure 1). With GEOMOD deforestation to pasture and deforestation to agriculture were merged into a single class "deforestation". Suitability maps for agriculture, pasture and forest were elaborated using multi-criteria method in IDRISI. Logistic regressions were carried out in order to find equations which give the probabilities of deforestation to pasture and to agriculture respectively as a function of slope, distance to roads, to settlements, to existing pasture patches and to existing agriculture patches. DINAMICA allows obtaining the more realistic simulated landscape.

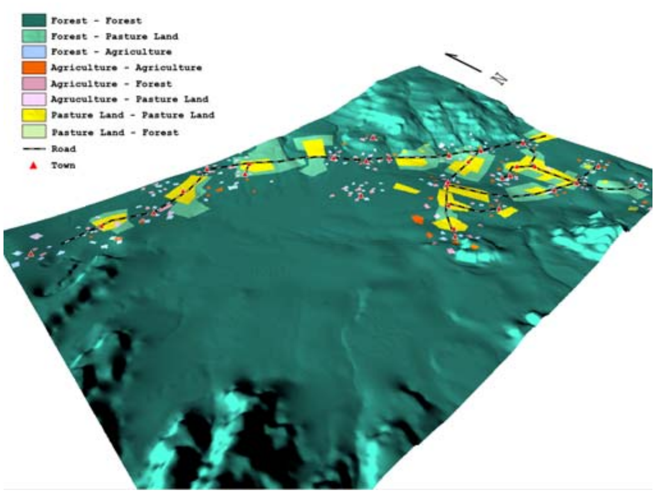

Figure 1. 3D representation of the "virtual" case.

4. CONCLUSIONS

Among the four reviewed packages DINAMICA is by far the more sophisticated package. In case that the modelling objective is to obtain a rapid simulation showing the more likely areas to change, CLUE-S or GEOMOD can be applied. The advantages of these two approaches are the simplicity of the modelling procedure. However, if the modeller pretends to carry out a more complex simulation (e.g. variation of transition rates during simulated period) or want to obtain realistic landscape patterns DINAMICA is the more indicated package. IDRISI´s CA_Markov does not present all the possibilities of DINAMICA but allows more sophisticated simulations than GEOMOD and CLUE. A recently released version of DINAMICA which allows the construction of more flexible models has not be evaluated in this study.

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