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Combination of process-oriented and pattern-oriented models of land-use change in a mountain area of Vietnam

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ABSTRACT

The tools and methods developed by different scientific communities to simulate the dynamics of land use have emphasised either processes or patterns of changes. Agent-based models (ABM) belong to the former category while many spatially explicit simulation models belong to the latter. These two different modelling approaches were jointly implemented at a study site in Vietnam to assess their respective strengths and weaknesses with respect to their capacity to support the formulation of land-use policy and to influence decision-making by multiple groups of stakeholders. SAMBA is a people-centred approach combining an ABM, a role-playing game and a geographic information system. Participatory simulations help elicit the rules of the ABM and calibrate the model, while the model supports the participatory exploration of land-use change scenarios over longer time periods. CLUE-s is a spatial simulation model which explores changes in land-use patterns within user-specified rules of permissible change and rates of change. Driving factors that influence changes from one land-use type to another are defined by combining spatially explicit data on land use and supposed driving factors in a logistical regression analysis. Alternatively, the decision rules that were revealed during the participatory simulations – with the role plays and the multi-agent modelling of the SAMBA approach – were incorporated in the CLUE-s model to provide more realistic estimates for the varying influence of land-use drivers. We checked the respective validity of the two models by applying them at the same site and comparing their outputs. As a result, no single approach was obviously superior according to the validation statistics. The three approaches turned out to be complementary in simulating land-use patterns, while providing different types of information. Integration of the two models into a rule-based version of CLUE-s helped reconciling data-driven statistical models and process-driven agent-based models in LUCC research. This new model reinforced the overall framework by facilitating the partnership between researchers from different scientific communities and between researchers and multiple groups of stakeholders. It may also better respond to the expectations of land users at different levels of the decision-making hierarchy.

1. Introduction

Over the past decades the mountain areas of Northern Vietnam underwent major socio-economic and environmental changes which had a major impact on land-use systems and patterns of human development (Donovan et al., 1997; NCSSH, 2001). Local diagnostic studies showed a large number of contrasted trajectories of land-use change that are difficult to

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capture in an explanatory model based on a single process (Rambo et al., 1995; Castella and Quang, 2002). In such a context dynamic modelling of land use/cover changes (LUCC) may help guide policy formulation (Costanza and Ruth, 1998). However, applying such an approach in the mountains of Vietnam is particularly challenging because of the diversity of natural and human environments and the rapid pace of change in recent years (Castella and Quang, 2002). Researchers are faced with three levels of constraints:

(i) accounting for rapid institutional changes and shifts in local rules,
(ii) linking local and regional studies to take into account the tensions between contextual understanding and the need to generalise to provide support for policy-making,
(iii) incorporating and managing the different sources of uncertainty into the modelling framework (e.g., uncertainty of data about shifting cultivation systems provided by remote sensing or household surveys, uncertainty about the behaviour of farming households who are in a constant situation of social learning and adaptive management).

There is no simple, uniform way to analyse and explain the dynamics of land-use change. Traditionally two approaches have been proposed to characterize LUCC: (1) a bottom–up, anthropologic, process-oriented approach based on household surveys and resource base inventory, and (2) a top–down, land evaluation, pattern-oriented approach based on remote sensing and census data (Geoghegan et al., 1998). These methods pertain to two different scientific traditions but have some features in common: they are usually interdisciplinary, problem-oriented and empirico-inductive. Their common constraint for scenario development and exploration of future land use is that they are not dynamic. Dynamic LUCC models have been developed to link these different scientific traditions (Fox et al., 2002; Rindfuss et al., 2004). Based on land evaluation approaches, spatially explicit land-use change models have been developed that start with an analysis of the location suitability for different land uses and allocate changes to grid cells primarily based on these suitability maps or based on the condition of neighbouring cells (Verburg et al., 2004). In the spatial approach, the basic units are plots of land, either polygons or pixels. Examples of this group of models are described in papers by Clarke and Gaydos (1998), Pontius et al. (2001), Verburg et al. (2002), Soares-Filho et al. (2002) and Mladenoff (2004).

In contrast, in the local, anthropologic approach, another group of models has been developed that recently have gained popularity in the LUCC scientific community. These models use the real actors of land-use change (individuals or institutions) as objects of analysis and of simulations and pay explicit attention to interactions between these 'agents' of change. Therefore, they are commonly referred to as agent-based models (examples include Röling, 1999; Bousquet et al., 2002; Parker et al., 2003; Bousquet and Le Page, 2004; Matthews, 2006; Grimm, 1999).

In this paper we present the application of well-known representatives of both model types in a heterogeneous mountain environment. The application of two different modelling paradigms to the same area is unique in the land-use and land-cover change literature and provides an opportunity to discuss the relative strengths and weaknesses of both approaches. In addition, this comparison enables us to show how spatially explicit models and multi-agent models can benefit from each other, i.e. by linking the underlying processes of land-use change with their resulting spatial patterns. In our comparison of the models, explicit attention is paid to the validation of the models. Validation of land-use models is a real challenge due to methodological and data constraints (Walker, 2003; Pontius et al., 2004b). Validation methods specifically designed to evaluate land-use models have only recently become available (Hagen, 2003; Pontius et al., 2004a). However, validation is essential to determine the ability of the models to be of use in a policy discussion. Finally, we discuss the potential contribution of our experience to the research agenda of the LUCC community with regard to the connection between micro-level behaviour of land users and macro-level structures and patterns (Geoghegan et al., 1998; Lambin et al., 1999; Rindfuss et al., 2004; Verburg and Veldkamp, 2005).

2. Application of two complementary approaches to link processes and patterns of LUCC

2.1. *"Pixelizing the social" with an agent-based model of LUCC*

In recent years agent-based modelling has become very popular in both natural sciences and social sciences (Bankes, 2002, see also articles published in the Journal of Artificial Societies and Social Simulation). Several authors have stressed its potential to investigate complex adaptive systems by modelling and simulating complex processes among stakeholders, as well as between social and ecological dynamics (Jiggins and Röling, 2000; Janssen, 2002; Bousquet and Le Page, 2004). Different approaches have been proposed to elicit the behavioural models of stakeholders and to capture them in a computerised multi-agent model of LUCC (d'Aquino et al., 2002; Becu et al., 2003; Boissau and Castella, 2003; Huigen, 2004). In situations of deep uncertainty where traditional analytical methods are less effective in providing support for policy-making (Lempert, 2002), participatory approaches combining ABM and role-playing games can be used in collective learning processes to facilitate dialogue among local stakeholders and to collectively explore scenarios of land-use changes (Bousquet et al., 2002; Bousquet and Le Page, 2004). Such a "companion modelling" approach (http://www.commod.org) was designed and implemented in Vietnam from 2000 to 2002 (Castella et al., 2005b).

The aim of the overall research programme was to understand the changes in land-use patterns that accompanied the shift from a centrally planned collectivised agriculture to a market-oriented family based agriculture in the 1990s in Bac Kan province located 150 km to the North of Hanoi. Understanding the underlying driving forces of this agrarian transition was essential to support local populations and decision makers and enable them to cope with the profound and rapid transformations of their biophysical and socio-economic environment (Castella et al., 2005a). The research process started with the selection of contrasted research sites in terms of agro-ecological diversity and integration to market. At each study site, which corresponded to one commune, a monograph study was conducted over a period of 1 year. Both processes and patterns of local changes in land use were investigated from the two perspectives described above, respectively: repeated household surveys combined with long-term anthropological observations and analysis of chronological series of remote sensing data. The monographs were further included in a comparative analysis that yielded a generic multi-agent model describing the proximate causes of LUCC over the whole province (Castella et al., 2005a) and detailed narratives describing local specificities and underlying mechanisms of LUCC (Castella and Quang, 2002). In order to capture the complexity of the most recent, accelerating changes in the context in which farmers make their decisions and to generalise the model from a single household to the village community and then to the whole province, the multi-agent model was further combined with a role-playing game (RPG).

The SAMBA[1] RPG has a game board and wooden cubes, and each cube represents a plot of land of 1000 m^2. Each face of the cube is a different colour which corresponds to one of the main types of land cover. When they are placed on the board with the appropriate colour facing upwards, the cubes form a picture that respects the proportions of the actual landscape. Ten villagers can take part in each game. Each player draws a card that describes his or her 'virtual' family for the duration of the game. The card also gives the family's food needs calculated in equivalent quantities of rice, as well as available manpower. Next, the players draw cards allocating them between zero and three 'cubes' standing for rice fields. At each round of the game, the player decides how he or she will use these fields next year and whether to transform forest into agricultural plots. At the end of each round, the players can see the result of the decisions they made since they receive coupons representing the equivalent in rice. They hand over to the 'bank' the number of coupons that corresponds to the food consumed by the family. They keep the rest which they can invest in different ways. If they are in debt, they can borrow from their companion players or from the bank. The game ends after six rounds, then players and organizers share their impressions.

In the 3 days that follow, the project team creates a computer model that reproduces exactly what happened during the role-playing game. In the model, farm household-agents make decisions about their production activities according to their capacity to satisfy their family's rice needs from their own paddies. The model is parameterised according to local specificities, e.g., soil quality, climate, speed of forest regeneration, and livestock reproduction. The players are shown the result and the interface of the multi-agent model is explained, along with the rules that were used to create it. The participants are then free to discuss and change the rules if they wish, and to create long-term scenarios (Boissau and Castella, 2003). In the resulting simulations the village landscape changes annually (i.e. at each annual time step of the computer model) according to the decisions made by the farmer-agents about the allocation of their production means to different income-generating activities and by rules determined by vegetation dynamics. The model was parameterised according to local specificities, e.g., soil quality, climate, speed of forest regeneration, and livestock reproduction. The SAMBA model was then successively initialised with data from each of the 221 villages of Cho Don District. The initial conditions were extracted from a geographic information system (GIS) (e.g., topography, soil characteristics, crop requirements, land use in 1990, and distance to residential areas) and a database generated from household surveys (e.g., population, ethnicity, gender, livestock characteristics). Special events, like land allocation to individual households or forest plantation projects, were triggered according to the date they actually took place in each village. At each time step, all village-level simulated maps were aggregated to create a district-level map (Castella et al., 2005b).

The main lessons from this experience are that participatory simulations combining RPG, ABM and GIS make it possible to acquire local knowledge, which is then integrated in a spatially explicit LUCC model. This methodology facilitated two-directional communication between scientists and local farmers, and also enhanced the dialogue within each group, i.e. among scientists from different disciplines and among farmers with different social or ethnic status. The close articulation between field work and modelling activities played a major role in linking scientific knowledge and local knowledge; the simulation questioned the stakeholders, whose answers were then incorporated into the model (Boissau and Castella, 2003). In spite of these advantages some constraints in using the method at the regional scale were identified, which can be summarised as follows:

(i) The time necessary to generate the empirical knowledge based on local studies limited the generalisation of the methodology beyond regional or provincial scales.
(ii) Generalisation by aggregation of village maps relies on the assumption that local resources are mainly managed by the local communities, which was verified in the context of Bac Kan province (Castella and Quang, 2002) but may not be the case in other contexts. In the SAMBA model, interactions between agents or spatial entities above the village level, e.g., effect of regional markets, road development, exchanges between villages (of water, capital, labour force), were thus considered as external factors influencing farmers' behaviours.
(iii) A consequence of the previous point is that decisional/hierarchical levels above the village community, i.e. decision makers at district, province and national levels, were not easily mobilised to contribute to participatory processes of land-use planning in which local communities were the key players (Castella et al., 2004). Therefore, they may not necessarily develop land-use policies that provide support for the scenarios discussed and agreed upon at the level of the community.

[1] The acronym "SAMBA" is formed from SAM (the French acronym for Mountain Agrarian Systems), the name of the project in which the methodology was developed, and "BA" meaning "three" in Vietnamese.

2.2. "Socializing the pixel" with a spatially explicit model of LUCC

The CLUE-s[2] modelling framework was applied to the same research site in Bac Kan province in order to tackle some of the issues mentioned above. A key objective was to rapidly develop a tool for regional land-use planning by applying an existing LUCC modelling package and by taking advantage of existing databases. CLUE-s belongs to the family of spatially explicit models of LUCC (Verburg et al., 2004). It is based on a combination of empirical analysis of land-use drivers by logistic regression and the dynamic modelling of land-use conversion (Verburg et al., 2002). Spatial variation in land use is assumed to be dependent on a variety of environmental and socio-economic components such as soil characteristics, climate and topography, while human factors determine where and why certain land uses change. In its standard configuration, CLUE-s utilizes empirical methods (i.e. multiple logistic regression analyses) to reveal how the spatial variation in land uses is related to these factors. To generate the regression equations, initially maps and multi-scale datasets were transformed into a grid with the same cell size as for the SAMBA application i.e. 1000 m^2. Each cell was characterised by a number of attributes such as soil type, climate data, population density, elevation, slope and accessibility. The dependent variables in the regression are seven land-use types from the 1990 land-use map. The regression coefficients are used to calculate the suitability of a certain cell for a certain land use type in the year of analysis. The demand module defines the land requirements for each land-use type at the regional (district) level without taking into account the spatial configuration within the area. This non-spatial input can be identified by an economic model, future policies, or by a linear extrapolation of the growth of the land-use area. Stability settings represent the elasticity of a certain land-use type to change in order to represent the differences in temporal behaviour of the different land uses. This factor can be calibrated based on the history of land-use, or in combination with expert knowledge. A conversion matrix identifies allows or prohibits land-use conversion or the minimum time length before a certain conversion may take place, e.g., in case of regrowth of natural vegetation or swidden cultivation systems. When running CLUE-s, different land uses are allocated to different cells of the simulation area according to the location suitability, stability settings and iteration factors that represent the competitive advantage of the land use types. Iterations are continued until the allocation is equal to the demand. By using different policy scenarios with CLUE-s, planners can thus define those areas that will remain stable or those with a high probability of change in the foreseeable future (Verburg et al., 2002; Nguyen et al., 2002).

Compared with other top–down modelling approaches CLUE-s was easy to implement because it did not require extensive data collection. A district-level GIS was already available for Cho Don District and complementary data were easily collected from the administration. Another reason for choosing CLUE-s was because policy-makers were expected to be actively involved in the scenario-development phase, and CLUE-s facilitates scenario development. Two factors played a key role in raising the interest of regional land-use planners: (i) the method had already been used in many different countries and environments and was therefore considered by the scientific community as scientifically sound, (ii) the data used by CLUE-s are the same as those generated by the local and regional administrations to manage the land and were thus considered by policy makers as more reliable than data generated from participatory processes conducted in a limited sample of villages (Castella et al., in press). Furthermore, the policy-driven modelling framework showed its relevance in tackling the development issues identified at the scale of the province (e.g. increasing rice needs with increasing population, cattle production versus reforestation, forest conservation).

Three months from finishing the collection of the spatial data, the first version of the CLUE-s model was available for Cho Don District and different scenarios could be discussed: (i) livestock/pasture land development in response to an increased demand for meat, (ii) forest expansion to reach the objective of 50% of the province covered with forest in 2010, and (iii) increasing population putting too much pressure on the upland land resources (Nguyen et al., 2002). This experience showed that CLUE-s could provide a platform for interactions between scientists and district stakeholders in the context of the Vietnam uplands. However, a number of constraints were identified during the development of the model application that are inherent to the modelling technique:

(i) The approach is data driven: if the information about a process cannot be inferred from the maps, it cannot be included in the model or simplifying assumptions need to be made. Therefore, inductive spatial modelling approaches are sensitive to the uncertainty of the land-use map, data quality, and also the discrimination of different land-use systems from satellite images has a strong influence on the model outputs.
(ii) In a period of agrarian transition, rapid changes occurred in local institutions and rules. We can thus expect a changing influence of the LUCC drivers over the period of simulation. Such changes in processes cannot be captured because the model parameterisation is based on an inductive analysis of land-use patterns at the start of the simulation.
(iii) The 'processes' inferred from the observed patterns are statistical associations relevant to pixels. Translation into concrete action requires an understanding of the underlying mechanisms of change at the level of individuals and groups.

A new version of the CLUE-s model was developed that explicitly incorporates knowledge from the study area, because much information on the processes of land-use change in the study area was available from the research underlying the development of the agent-based approach. The standard implementation of the CLUE-s model based on suitability maps for the different land-use types derived from a logistic regression analysis that relates observed land use at

[2] CLUE-s stands for Conversion of Land Use and its Effects (Version CLUE-s2.4; http://www.cluemodel.nl).

the start of the simulation to variation in socio-economic and biophysical factors. Decision rules equivalent to those used in the ABM were used to define land suitability for different types of cropping, instead of defining the suitability maps from logistical regressions. In addition, the observed land-use practices in the area were translated into conversion elasticities and more specific settings of the conversion matrix. In the standard implementation, all conversions are assumed to be possible, while in the rule-based version all unrealistic conversions were excluded or related to a minimum succession length (e.g., the minimum time period for fallow or forest regrowth).

This rule-based version of the CLUE-s model was expected to perform better than the regression-based version in a context of high uncertainty due to both data quality and the rapid pace of change. It is important to measure whether it would provide more context-relevant simulations, and thus be more consistent with local knowledge.

3. A validation procedure to assess the performance of the different LUCC models

The outcomes of the two modelling frameworks were compared in order to assess their relative performances and to identify the situations in which they could be useful. In the case of SAMBA, the modelled process had already been validated by local stakeholders during specific sessions of the role-playing game (Castella et al., 2005b). Villagers gave verbal confirmation that the model satisfactorily represented both the patterns of landscape changes that had occurred during the simulation period, and the local processes of natural resources management that triggered these changes. The second stage of the validation procedure consisted of a map-to-map comparison over the entire Cho Don District (Fig. 1). Six land-use classes were identified from the classification of SPOT satellite images for 1990 and 2001: forest, shrub, upland crops, wetland paddy, residential, and grassland. Some land-cover classes, like shrub and forest, were difficult to distinguish in the satellite imagery because of ruggedness of the mountainous relief, patchiness of the landscape, the mosaic of swiddens, different stages of fallow regrowth, and secondary vegetation on degraded land (Castella and Quang, 2002). However, the land-use changes that occurred during the period of investigation have a magnitude larger than the uncertainty due to data inaccuracy. The 1990 and 2001 land-use maps resulting from image classification, hereafter referred to as "reference maps", were compared in terms of quantity of change and location of change with simulated outputs from the three models, i.e. SAMBA, regression-based CLUE-s and rule-based CLUE-s. These models had been initialised with the 1990 "reference map". Pontius et al. (2004a) suggest comparing the model runs with a simple model that assumes complete persistence of land use across the time period (i.e., no change). This model is referred to as the "null model". Pontius et al. (2004a, in press) indicate that it is often difficult for land-use models to outperform the null model.

3.1. *Multi-resolution validation procedure*

A validation procedure specifically developed to compare discrete, spatial data, named "multi-resolution goodness of fit" (Costanza, 1989; Pontius et al., 2004a), was applied to the set of land-use maps presented in Fig. 1. The statistical technique

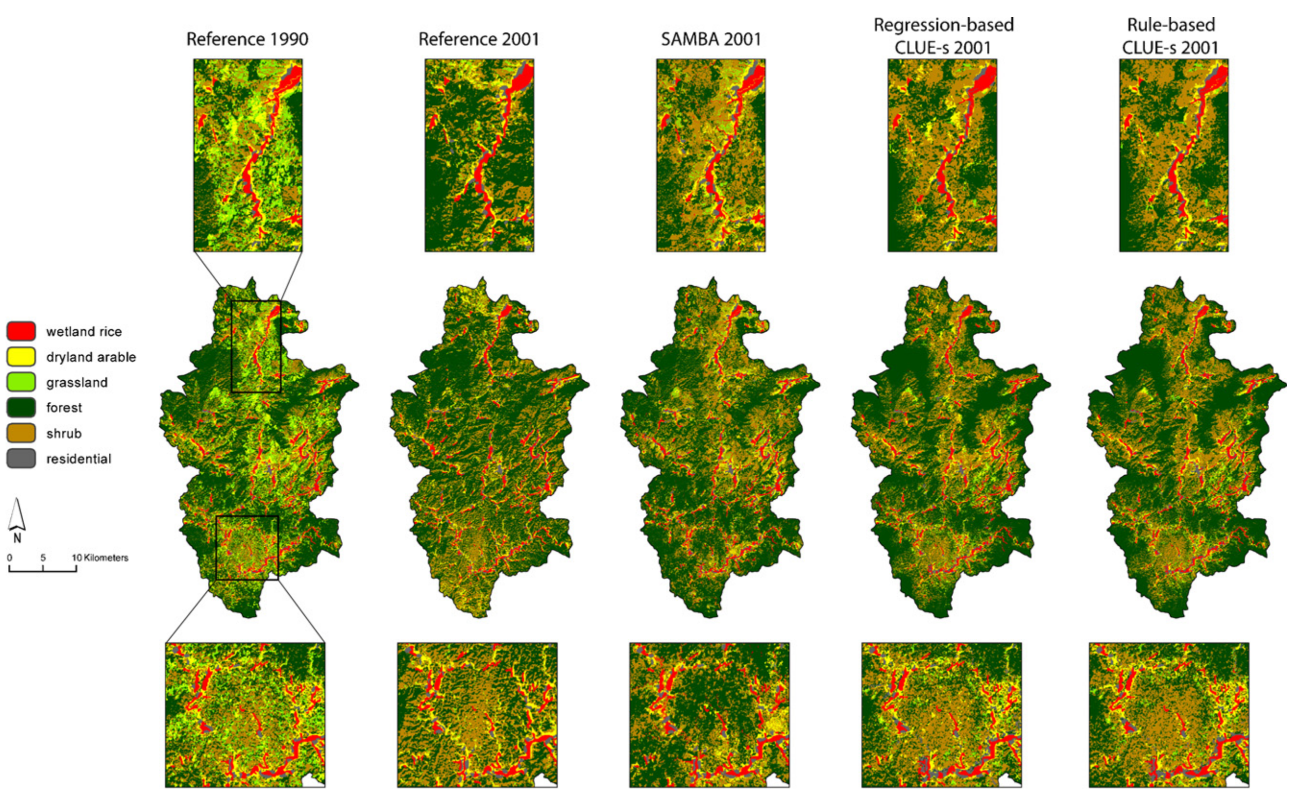

Fig. 1 – Comparison of reference and simulated land-use maps for Cho Don District, Bac Kan Province.

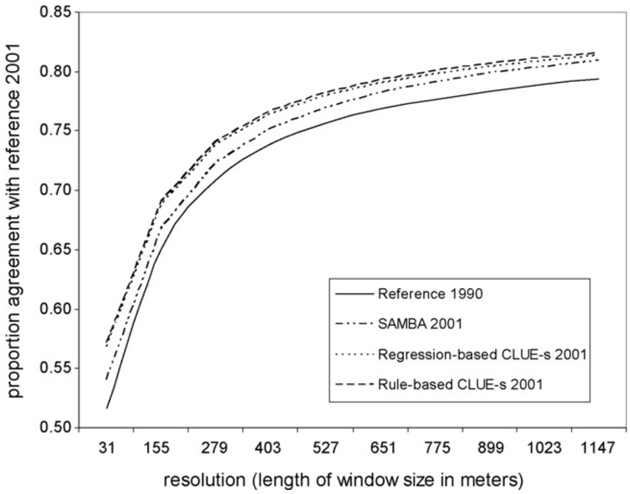

Fig. 2 – Proportion agreement at multiple resolutions for the three LUCC models and the reference map of 2001 (note that the entire study area measures 968 × 1628 cells of 31 m × 31 m each).

compares the accuracy of the LUCC model to the accuracy of its null model at multiple resolutions. The accuracy of the LUCC model is the percent of pixels with land-use classes in agreement between the reference map of 2001 and the simulated map of 2001. It is expressed as proportion agreement in the vertical axis in Fig. 2. The accuracy of the null model is the percent of pixels in agreement between the reference map of 1990 and the reference map of 2001. The proportion agreement is also evaluated at coarser resolutions using an expanding 'window' as is indicated on the horizontal axis in Fig. 2 from one pixel on the left to coarser resolutions to the right. Differences in spatial allocation within such a 'window' are ignored, e.g., when in both maps within a 2 × 2 pixel window 3 pixels are classified as forest and 1 as agriculture this is considered as agreement irrespective of the spatial configuration of the land uses within this window. Overall agreement increases as the resolution becomes coarser for both the LUCC model and its null model, because location disagreement becomes agreement as the resolution becomes coarser. Overall agreement increases to the level at which the only remaining disagreement is quantity disagreement, when the entire study area is in 1 large pixel.

In Fig. 2, the LUCC models are more accurate than the null model at all resolutions. The Ft values in Table 1 represent a weighted average of the agreement over the window size varying between 1 pixel (31 m) and 37 pixels (1150 m). The weighted average gives most weight to the small window sizes following Costanza (1989). Ft is generally used to determine an overall degree of fit between two maps across multiple resolutions. The graph (Fig. 2) and Ft values (Table 1) show that CLUE-s performs better than SAMBA at all resolutions with slightly better accuracy for the rule-based version of CLUE-s than for the regression-based version. However, these results should be analysed in more detail by investigating some specificities of the modelling processes for both SAMBA and CLUE-s.

Table 1 – Multiple resolution goodness of fit for the three LUCC models and the reference model

Model run	Multi-resolution goodness of fit (Ft)
Reference 1990 (null hypothesis)	0.686
SAMBA 2001	0.702
Regression-based CLUE-s 2001	0.718
Rule-based CLUE-s 2001	0.721

For proper model validation, the validation data set should be completely independent from the calibration data. No information obtained after the initial year of simulation should be used (Pontius et al., 2004a). Such a situation resembles a simulation of future scenarios. However, complete ignorance of the processes during the validation period is difficult to achieve. In the SAMBA model, for example, the information concerning the date of forest allocation to households and the percent of land allocated to individual farmers in each village was based on interviews made in 2000 and 2001. Interviews were also the source of information concerning yields of main crops, the labour force required for main cropping practices, and the prices of the main commodities. Furthermore, the occurrence of special events like land allocation to individual households or forest plantation projects, was triggered according to the date they actually took place in each village. Thus, the assessment of the results for the modelling run from 1990 to 2001 should be interpreted as a measurement of the goodness of fit of some combination of calibration and validation, rather than exclusive validation, since the model uses post-1990 information to simulate land change.

The regression-based version of CLUE-s bases its allocation rules solely on the analysis of the 1990 data and is therefore independent of 2001 data. However, the demand function used in this application of CLUE-s is a linear interpolation of start and end aggregate quantities of the land-use types. So quantity of each simulated land type is always correct and not predicted, and in this case, only spatial patterns are simulated and validated. On the other hand, SAMBA also predicts quantity, so it is more difficult to obtain satisfactory validation for SAMBA. In this case however, quantity is almost correctly predicted by SAMBA (disagreement of 2.6% only); therefore, the models are comparable for the spatial validation measurements in Fig. 2. But it is important to note that SAMBA predicted quantity correctly and CLUE-s did not predict quantity at all.

3.2. *Visual and zonal validation procedures*

Apart from the classical grid-based validation method, alternative validation techniques can be used to assess to what extent the methods are able to capture the typical structure of the landscape. Visual comparison of the reference and simulated maps revealed that the two modelling frameworks perform differently depending on the typical structure of the landscape. Three different sites were extracted from the land-use maps and are presented in Figs. 1 and 3. Two of the sites are exemplary for the mountain landscapes in the northern part of the district while the third site is representative of the more densely populated southern part of the district. The mountain landscapes can be characterised as elongated watersheds

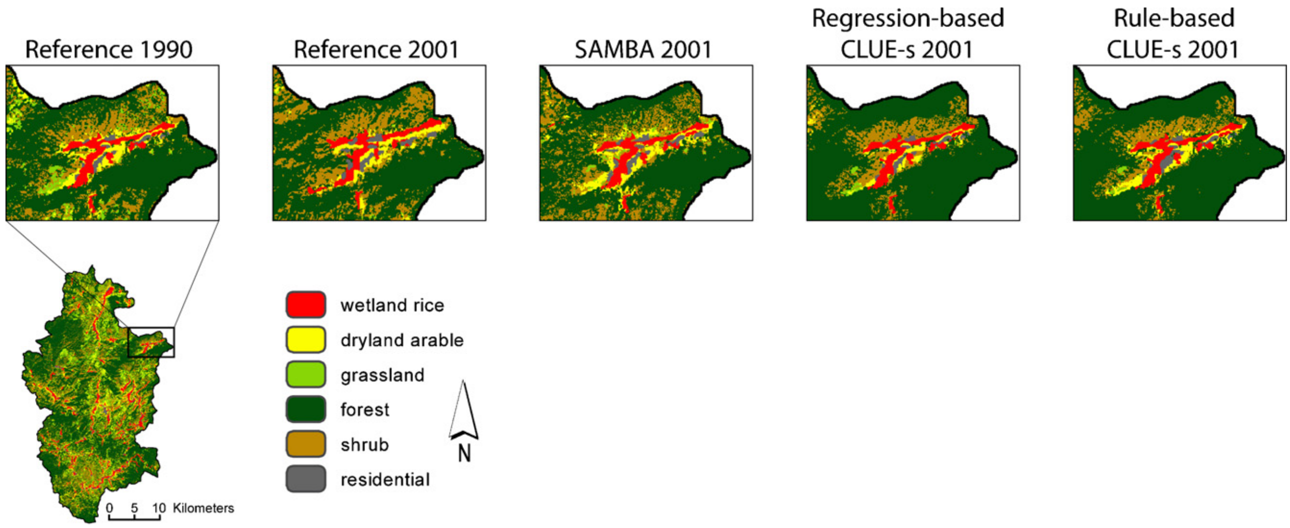

Fig. 3 – Comparison of reference and simulated land-use maps for a research site in Cho Don District, Bac Kan Province.

that support a tiered structure of land cover with forest at the top and then, going down the hill, a mosaic of shrub and upland crops with an increasing proportion of the latter as one approaches the narrow valley bottom. In such a tiered landscape, farmers decide where to convert land use depending on the distance of the plot from their home and its location on the watershed. As the villages are located in the valley bottom along the road near irrigated paddies, farming activities decrease in intensity with an increase in altitude. The visual comparison of the mountain landscape in the northern part of the district (Fig. 1) shows that both models underestimate the regrowth of forest on the slopes. However, in another part of the mountainous area (Fig. 3) the CLUE-s model overestimates regrowth of forest on shrubland, whereas the SAMBA model captures the structure of land use better. The opposite is true for the relatively flat area in the southern part of the district (Fig. 1) where CLUE-s is better able to capture the land-use pattern. This visual comparison shows that the performance of the models varies considerably throughout the study area. The measure of validation only gives an indication of the overall model validity.

From the visual comparison it was not possible to say which model is better able to capture typical structures of the landscape. Consequently a validation procedure was used to test which model is best able to capture the typical organisation of land uses as a function of the distance to the homestead or village. For eight ring-shaped zones located at a distance of 500 m from each other around the village centre (Fig. 4) and for each model run we calculated the fraction of each land-use type in each zone. Fig. 5 shows these values for upland crops in a scatter plot with the successive 500 m ring-shape areas along the x-axis. Both models tend to over predict the area of upland crops near the villages and under predict the area far from the villages, because both models use suitability maps that indicate the highest suitability of the land near to the villages. The SAMBA model and rule-based CLUE-s perform better than the regression-based CLUE-s in the intermediary area where accurate simulation is the most important to capture the complex mosaic of land-use types under swidden systems. The over prediction of CLUE-s near the villages can be attributed to the land-tenure situation which limits the activities of some land owners in this zone. The tenure structure is commonly not accounted for in pixel-based approaches like CLUE-s. A scatter plot with the predicted and observed fraction of all land

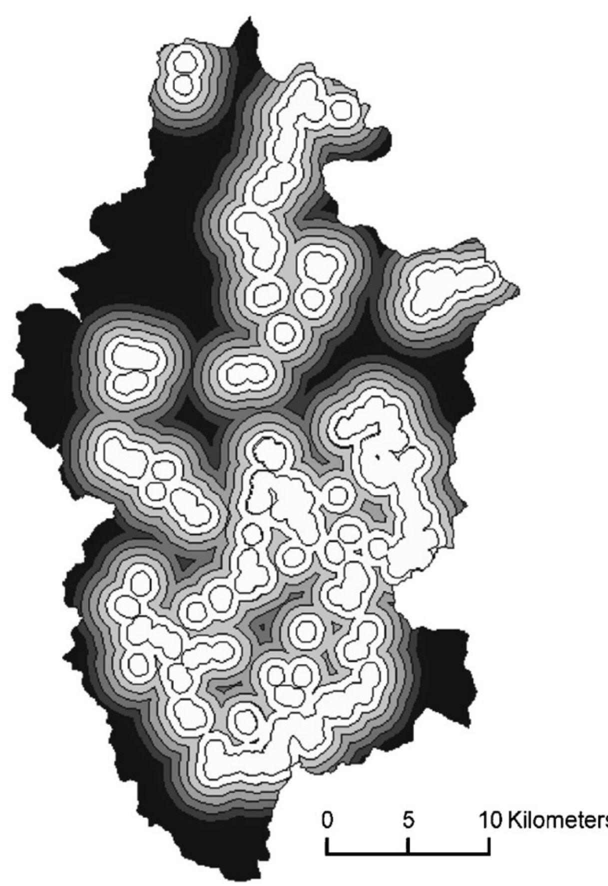

Fig. 4 – Map of Cho Don District showing zones with different distances from the villages; the zones are located 500 m from each other.

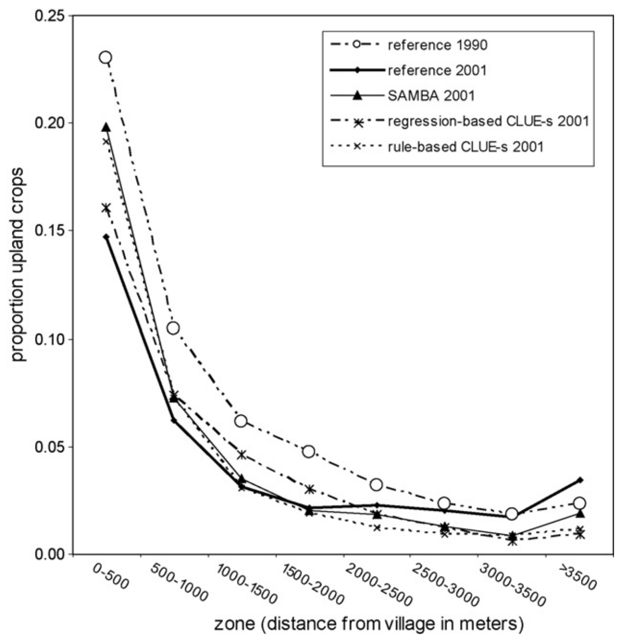

Fig. 5 – Proportion of upland crops for the different zones structured according to the distance from the village.

uses in each of the zones is shown in Fig. 6. The mean absolute error was calculated for each of the model runs, the higher the mean absolute error, the worse the model performed (mean absolute error was chosen instead of mean squared error following Willmott and Matsuura, 2006) Under this validation procedure SAMBA has a much lower error rate than both CLUE-s runs, confirming that SAMBA better captures the landscape structure related to the location of the villages.

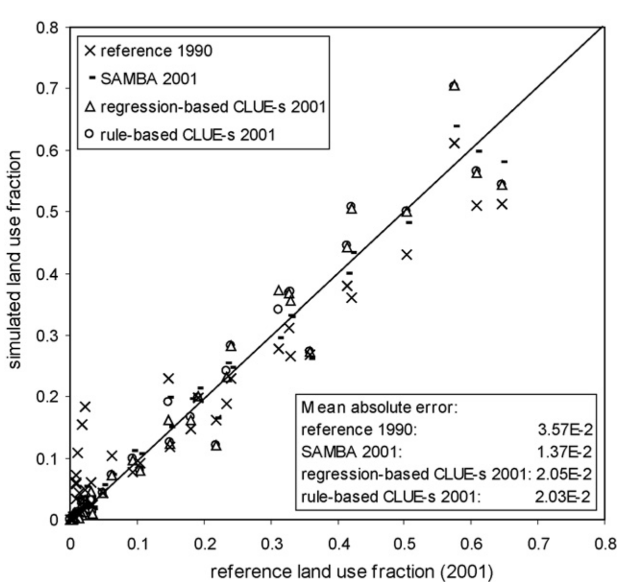

Fig. 6 – Simulated fraction of land occupied by the different land use types for each zone (at different distances from the village) and indication of the mean absolute error; the line $y = x$ is indicated for reference.

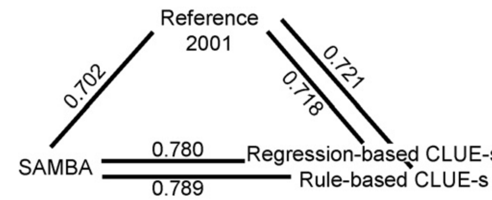

Fig. 7 – Multi-resolution goodness of fit (Ft value of map similarity) for the different model runs and the reference land-use data in 2001.

The main lessons we could draw from this experience is that model validity can be measured at different scales and with different methods. Each validation procedure tests accuracy for different properties of the models: the location of changes for the multi-resolution goodness of fit, the typical structure of the landscape for the zonal validation procedure, and farmers' decision-making processes for the actor-based validation with the role-playing game (Boissau and Castella, 2003). Both SAMBA and CLUE-s models outperformed the null-model in both validation methods. It is worth mentioning that the results of SAMBA and CLUE-s were more similar than the results of each of the models compared to the reference map of 2001 when measured by the multi-resolution method (Fig. 7). This can probably be explained by the fact that both models rely on landscape data and environmental variability in their simulations of LUCC while the actual land-use decisions may also be modified by land-tenure conditions and diversity in household characteristics not accounted for in the models as well as arbitrary considerations in land use decision-making. From Fig. 7 it is obvious that the results of the SAMBA model are more similar to the rule-based version of CLUE-s than to the regression-based version due to the use of similar suitability maps.

4. Discussion

The comparison and validation of different modelling approaches used for the same study area and data set showed that it is not possible to say unambiguously which model is best able to simulate land-use patterns. The multi-resolution and zonal validation methods provided different results: SAMBA better represents the land use structure related to villages, while CLUE-s captures the overall pattern better. The contradiction between the two validation methods reveals the difference in modelling technique and indicates that a single universal validation method may not be applicable. Furthermore, these measurements provide an overall fit of the model, while the performance is very different in different parts of the region. Validation by quantitative methods as presented above evaluates only spatial prediction quality, not process description quality. The choice of validation methods thus clearly depends on the purpose of the study. It should be mentioned that, in addition to the two validation methods used in this paper, other quantitative validation methods are available. When landscape structure is the prime interest of the simulations it may be useful to validate the simulations based on spatial metrics or landscape indicators (Herold et al., 2005; Brown et al., 2005). The primary advantage of using spatial metrics or landscape indicators is that they describe the patterns in a way that relates them to the ecological impacts of land-use change (Jenerette and Wu, 2001).

When the objective is to visualise LUCC rapidly, a basic CLUE-s model, based on careful statistical analysis of available data layers, performs better than the null model for this study area. However, we learned less about the driving factors and processes of land-use change during the construction of this simple model and the dynamics over time were less realistic than with SAMBA. But the implementation of the regression-based CLUE-s application took less than 3 months (once the data were collected and compiled) while the participatory approach supported by the SAMBA model took almost 3 years. Therefore, the two approaches should not be seen as competing but as complementary approaches in reconciling process and pattern in LUCC research and informing stakeholders about potential future land use dynamics. The CLUE-s approach reveals some of the most important relations between spatial and temporal variability of the landscape while the SAMBA approach tries to unravel the different processes that underlie these different patterns. The pattern-to-process step in modelling was to add knowledge of the area to an "empirically" calibrated model, i.e. the rule-based version of CLUE-s (Nagendra et al., 2004; Verburg, 2006).

Both models have a high level of uncertainty as is indicated by the validation results. However, it should be noted that the validation data, i.e. reference map of 2001, have a high level of uncertainty as well, e.g., classification errors in the reference maps. In particular distinguishing shrubland and (open) forest from remote sensing data is extremely difficult in a mountainous terrain. Therefore, the validation results may over- or under-estimate the actual error in the representation of the land-use change processes by the models depending on the way in which the data errors propagate through the model results. This will be different for the different model types. In the regression-based CLUE-s application, the processes are directly induced from the data, so the data errors limit the description of the processes. The processes of SAMBA are subject to errors in interpretation/perception of the stakeholders. However, in a context of rapid change the usefulness of the models should be measured not by their capacity to predict land changes but by their ability to adapt to changing rules and to support stakeholders in their exploration of scenarios of LUCC (Castella et al., in press).

The legitimacy of modelling approaches using complex adaptive systems, like agent-based models, results from the scientific soundness of the model and the understanding local stakeholders can gain about the model parameters and rules. In SAMBA, stakeholders' trust in the model was based on repeated use with different groups of stakeholders and on the combination between the ABM and the role-playing game. The gaming-simulation sessions helped elicit the rules of the ABM and enriched the model, while the model supported the participatory exploration of land-use change scenarios over longer time periods. The legitimacy of spatially explicit LUCC models is rooted in their scientific empirical soundness and reproducibility, which is assessed by different validation procedures, and also by their repeated use in very different circumstances and for different research sites. The combination of these two complementary approaches of LUCC can empower both local and regional land-use planners. Increased trust in the two modelling frameworks is gained when simulations from process-oriented models and pattern-oriented models converge, when models relying on different research paradigms agree with each other.

5. Conclusions

The main lesson we learned from applying two different LUCC modelling frameworks to the same research site is that the choice of model has important implications in terms of the specific aspects of land-use changes that can be investigated. Statistical models and ABM were very complementary in capturing both patterns and processes of LUCC in an interactive fashion. Of course the choice of a model depends on the objective of the study and on available resources.

The regression-based CLUE-s is based on statistical associations that do not necessarily represent the processes of change. Therefore, it is difficult to implement scenarios in which some of the processes change or new crops are cultivated in the area. SAMBA or the rule-based CLUE-s would be able to explore such scenarios. For policy use, the regression-based CLUE-s allows rapid exploration and visualisation of scenarios and serves as an early-warning system for potential land-use conflicts. It can also be useful to evaluate spatial policies, e.g., trade-off between a protected area and other areas. On the other hand, SAMBA and rule-based CLUE-s have shown their relevance in analysing alternative policies and guiding decision-making to impact landscape pattern and sustainability.

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