CLUE: AN INTEGRATED, GIS-BASED MODEL TO SIMULATE THE DYNAMICS OF LAND USE IN DEVELOPING COUNTRIES

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ABSTRACT

Changes in land use/cover are the major determinants of changes in our natural environment through numerous interactions between land use/cover and the atmosphere, aquatic systems and surrounding land. Land use changes are clearly driven by human activities. However, the actual location where land use changes take place is determined by biophysical conditions as well.

Spatially explicit assessments of environmental change are needed because environmental change does not affect all places similarly, differential impacts and abilities to respond creates winners and losers in this change. The identification of the dynamics giving rise to vulnerability of people and places in the face of global change is therefore essential.

A GIS-based modeling approach (CLUE: the Conversion of Land Use and its Effects) is developed which includes the analysis of relations between land use and its (proximate) driving factors as well as the dynamic simulation of near-future land use changes by a numerical model. Relations between land use and its (proximate) driving factors, including both biophysical and human factors, are quantified by multi-variate statistical techniques. These relations are used in a dynamic model that explores changes in the land use pattern under near future conditions of demand for agricultural production and other land utilization. Within the modeling procedure explicit attention is given to competition between different land use types and top-down and bottom-up interactions. Several applications of this approach are described in this paper.

1. INTRODUCTION

Land cover is defined as the layer of soils and biomass, including natural vegetation, crops and human structures that cover the land surface. Land use refers to the purposes for which humans exploit the land cover (Fresco, 1994). Land cover change is the complete replacement of one cover type by another, while land-use changes also include the modification of land-cover types, e.g., intensification of agricultural use, without changing its overall classification (Turner II *et al.* 1993).

Land-use changes, mostly driven by human activities, result in global environmental change (Riebsame *et al.* 1994; Vitousek *et al.* 1997; Houghton, 1994; Tinker, 1997). The individual activities leading to land-use changes meet locally defined needs and goals, but aggregated they have an impact on the regional and global environment (Turner II, 1994; Ojima *et al.* 1994). Changes in land use affect biodiversity, water and radiation budgets, trace gas emissions and other processes that, cumulatively, affect global climate and biosphere.

Land-use change is directly linked to the theme of transition to a sustainable world. With origins in the Brundtland report and increasingly embedded in global change science agendas, the overarching concern is achieving this provisioning in a warmer, more crowded, and more resource demanding world characterized by unexpected and extreme events. This transition requires an improved understanding of the trajectories of land-use change that invoke positive or negative human-environment relationships (Turner II *et al.* 1987; Holling *et al.* 1996).

A better understanding of the processes of land-use change is essential to assess and foresee the effects of land use change for ecosystems and society. Greenhouse emission inventories and reduction objectives need to include the foreseen changes in emission source strengths as a consequence of land-use change, rates and patterns of land-use change need to be understood to design appropriate biodiversity management. Priority areas of land use change need to be identified to focus land use planning at the appropriate regions.

2. PROBLEM STATEMENT

Land use and cover change are the result of many interacting processes. Studying the dynamics of these processes requires an understanding of the two fundamental issues in land use change research, namely, integration of human and environmental driving factors of land-use change and the study of system behavior over a range of spatial scales. Each of the identified human-environment interaction processes operates over a range of scales in space and time. Many interactions and feedbacks between these processes at different levels of organization occur. If for all processes involved with land use and land cover change these hierarchies must be distinguished as well as their mutual interactions the situation gets enormously complicated. Researchers in the field of land-use studies share the formidable task of coming to grips with the complex causal web linking social and biophysical processes (Turner II, 1997). Even more challenging are models of land use change that provide tools for understanding the causes and consequences of rapid land-cover changes. Models are useful for disentangling the complex suite of socio-economic and biophysical factors that influence the rate and spatial pattern of land-use change and in estimating the impacts of changes in land use. Furthermore, models have the capability to make predictions of the possible developments of the land-use system into the future.

This paper presents an approach for studying and modeling the dynamics of land-use change in a spatially explicit way, directly linked to Geographic Information Systems, the method is illustrated with a number of examples from case-studies.

3. METHODS

The CLUE methodology (Veldkamp *et al.* 1996; Verburg *et al.* 1999a) is based on theories about the functioning of the land-use system derived from landscape ecology (Holling, 1992; Levin, 1992; Turner *et al.* 1992). Natural ecosystems have large correspondences in structure, function and change with land-use systems and the social systems underlying changes in land use. Social systems and agro-ecosystems are, just like natural ecosystems, complex adaptive systems which can be described by theories and methodologies developed in ecology (Holling *et al.* 1996).

The CLUE methodology is applied over a wide range of case-studies, including the countries of China and Ecuador and the complete Central-American region (Verburg et al., 2000b; Kok et al., 2000; Kok and Winograd, 2000). More recently new applications are developed for smaller regions, such as the Northern Atlantic Zone of Costa Rica (Kok and Veldkamp, 2000) and Sibuyan Island in the

Philippines. These different scales of analysis request for a slightly different approach to land use change analysis. An essential difference is the data representation: in most grid-based approaches land use is defined by the most dominant land use type within the grid cell. However, in the applications for large areas we have represented land-use by designating the relative cover of each land use type in each grid cell, e.g. a grid cell can contain 30% cultivated land, 40% grassland and 30% forest. This data representation is a direct result of the information contained in the census data that underlie the approach. For each administrative unit census data denote the number of hectares devoted to the different land use types. Moreover, data representation for a study with a large extent and, corresponding coarse resolution, would result in a large bias when data are represented by the dominant land use type in a grid cell. For the applications in small areas the situation is different. Here we based our data on land use maps or Remote Sensing images that denote land use types respectively by homogeneous polygons or classified pixels. At this scale it is also more common that only one land use type occupies one unit of analysis. These two different data representations are illustrated in Figure 1. The modeling approach chosen for each of these two data representations is very similar and based on the same characteristics; small modifications are made to allow the different data structures.
The modeling method can be subdivided into two parts. The first part, the multi-scale spatial analysis, aims at establishing relations between land use and its driving factors taking scale dependencies into account explicitly. The second part aims at dynamic modeling.

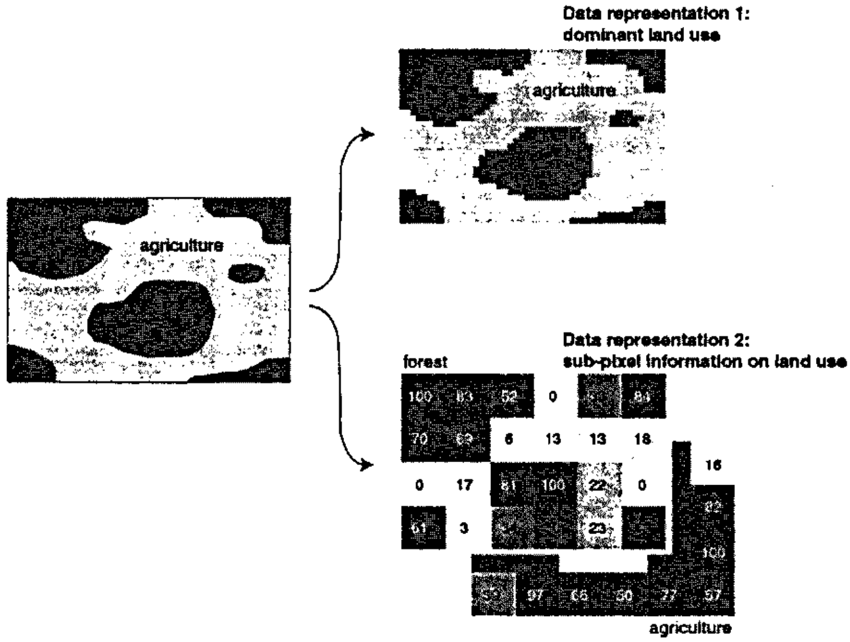

Figure 1: Two different data representations used in the modeling approach for respectively small case-studies and national/continental scale case-studies

The multi-scale analysis of the driving factors of land-use change is based on the analysis of spatial patterns of actual land-use. Except for areas with minimal human influence, these patterns reflect the result of a long history of land-use change and contain, therefore, valuable information about the relation between land use and its driving factors. Because it is assumed that the relations between land-use and driving factors are extremely complex due to scale dependencies, interconnections and feedbacks no attempts are made to unravel the individual processes. Instead, empirical relations between land use and its supposed determining factors explain the observed pattern of land use, e.g., through regression analysis. Another characteristic of the approach is that no a priori levels of analysis, e.g., landscape or regional level, are superimposed. Instead, the analysis is repeated at a selection of artificial resolutions, imposed by the gridded data structure and calculated by aggregation or focal functions. An example of the results of such an analysis is presented below. These results are of interest by themselves and can be subjected to extensive interpretation. They can, however, also directly be used for the dynamic modeling of near-future land use changes.

The dynamic model (Veldkamp *et al.* 1996; Verburg *et al.* 1999a) uses the derived multi-scale relations between land-use change and its driving factors as a direct input for modeling. The modeling approach has the following characteristics:

- All simulations are made in a spatially explicit way so that the geographical pattern of land use change is resulting. The spatial resolution of the simulations is dependent on the extent of the study area and the resolution of data available for that study area.
- Allocation of land use changes is based on the dynamic simulation of competition between different land use types. Competitive advantage is based on the 'local' and 'regional' suitability of the location and the national level demand for land use type related products (e.g., food demand or demand for residential area).
- The 'local' and 'regional' suitability for the different land use types is determined by quantified relations between land use and a large number of explanatory factors derived in the multi-scale analysis described above.
- Different scenarios of developments in land-use can be simulated. At the national level scenarios include different developments of agricultural demands that can be determined on the basis of developments of consumption patterns, demographic characteristics, land use policies and export volumes. At the sub-national level different restrictions towards the allocation of land use change can be implemented, e.g., the protection of nature reserves or land allocation restrictions in areas susceptible to land degradation.

4. FINDINGS

The CLUE model was first developed for, and applied to, Costa Rica (Veldkamp *et al.* 1996). Recent and current applications are those for Ecuador (de Koning *et al.* 1999a), Central America (Kok and Winograd, 2000), China (Verburg *et al.* 1999b) and Indonesia (Verburg *et al.* 1999c).

4.1 Analysis of driving factors for China

The above described method was used to study the (proximate) driving factors that determine the spatial distribution of land-use in China. These driving factors were studied by systematically varying the spatial extent and resolution of analysis. The extent is varied between the country as a whole, and a subdivision in 8 delineated regions. The resolution of analysis was increased in 6 steps from grid-cells of 32x32 km (~1000 km^2; n=9204) to grid-cells of 192x192 km (~36800 km^2; n=258). For these different scales of observation the land-use distribution (represented by the relative area covered by the individual land-use types in the grid cells) was related to a large set of potential driving factors by correlation and regression analysis. As an example of the results, reported by (Verburg *et al.* 2000a) the five explanatory factors having the highest correlation with the distribution of cultivated land are presented in Table 1. The analysis demonstrated that for the country as a whole the pattern of cultivated land corresponds best with the agricultural population distribution. When the extent of analysis is decreased, by repeating the statistical analysis for separate regions within China, agricultural population is not always the most important explanatory variable anymore. Especially in the regions

Northeast, East and South the pattern of cultivated land is most related to the geomorphology of the area. Larger differences between the analysis for the country as a whole and the individual regions were found for the less dominant factors.

The effect of resolution was studied by comparing the results of a correlation and regression analysis at six different artificial aggregation levels. For most determining factors of the land use distribution the correlation coefficient increases with grain size. This increase in correlation coefficient may have been caused by area aggregation, which reduces the variability. However, the correlation coefficients were not inflated consistently with successive aggregation and for the different variables. Sometimes the increase in correlation coefficient at a higher level of analysis can be explained by the influence that a certain driving factor, such as a city, has on its surrounding area. With the increase in grain size, an increasing part of the cultivated land around a city falls within the same grid-cell as the urban population, yielding high correlation between the two parameters that were only slightly correlated at a more detailed resolution.

Whole country (n=9204)	Northeast (n=764)	North (n=674)	Northwest (n=3361)	East (n=336)
Agric. population	Max. temperature	Mountains	Agric. population	Total precipitation
Agric. labor	Mountains	Agric. population	Agric. labor	Mountains
Total population	Deep soils	Slope	Rural labor	Elevation range
Rural labor	Level land	Agric. labor	Total population	Well drained soils
Soil suitability R-S1	Agric. population	Plain land	Loess	Bad drained soils

Central (n=554)	South (n=547)	Southwest (n=1098)	Plateau (n=1870)
Mountains	Mountains	Agric. labor	Rural labor
Agric. population	Slope	Agric. population	Agric. labor
Total population	Max. temperature	Rural labor	Agric. population
Plain land	Avg. temperature	Total population	Total population
Well drained soils	Mean elevation	Mean elevation	Urban population

Table 1. Most important explanatory factors for the distribution of cultivated land based on Pearson correlation coefficients (all significant at $P<0.0001$, n=9204)

4.2 Modeling results for Java, Indonesia

The island Java (Indonesia) is unique because of its high population density (> 800 p km^{-2}) and intensive agriculture. The high population density has put a large pressure on land resources for a long time. The process of economic growth and increasing population numbers has shifted agricultural expansion to the outer Indonesian islands while Java is changing into a more urbanized society. With the CLUE model a scenario is evaluated which is assumed to be representative for future land use changes in Java. The scenario is based on developments expected by the World Bank (1992). As this World Bank study was made before the recent Asia Crisis it projects a continuation of economic growth. The major land use change represented in this scenario is caused by an increasing demand for non-agricultural land, e.g. land for urban and manufacturing development.

Also the expanding number of farm families in the rural areas will require new land for house plots. Based on demand-supply studies it is expected that within agriculture there will be shifts away from paddy towards horticultural crops and other cash crops. The expanding and wealthier urban population will demand more fruit and vegetables, of which the larger part is expected to be cultivated in Java. The results of the scenario simulations are presented in Figure 2. The maps indicate the major patterns of land use change as they are predicted for the period 1994-2010. The most obvious pattern is the decrease in paddy fields in the northern coastal plain of Java, due to increases in housing area, estate crops and some increases in dryland agriculture. Other hot spots of land use change are found in the neighborhood of the urban centers of Surabaya and Bandung, the major cities of Java. The model also predicts some land use changes in the presently undeveloped areas in the western and southern part of West Java. When summarized by agro-ecological zone most changes in land use are found in the lowlands. Land use dynamics in the uplands are much lower, except for shifting cultivation.

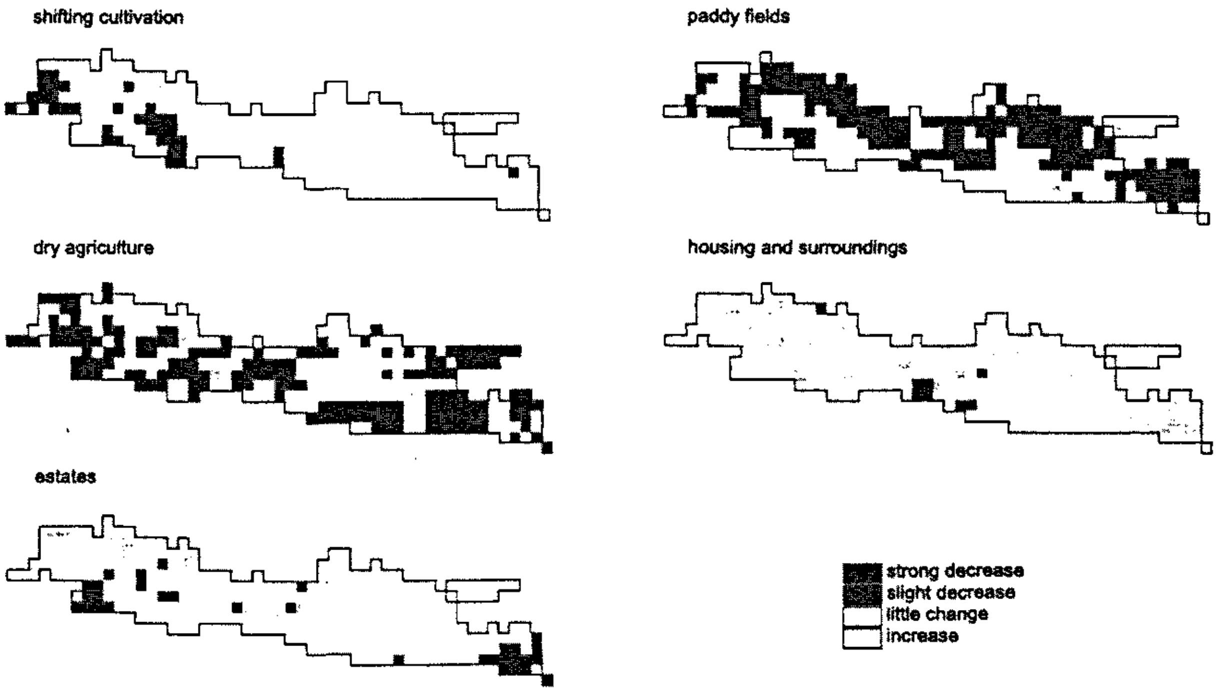

Figure 2: Simulated changes in land use between 1994 and 2010

4.3 Land use change and its effects for nutrient balances in Ecuador

For Ecuador, with a total extent of 260 x 10^3 km^2, a minimum cell size of 9 by 9 km was used (De Koning et al., 1999a). The reference year 1991 was used to quantitatively determine the drivers for the land use types permanent crops, temporary crops (annuals), grassland and natural vegetation. The country was stratified into three regions: the Andean mountain range, the tropical coastal lowland (west of the Andes) and the Amazonian lowland (east of the Andes). A variety of scenarios was formulated for the period 1991-2010. At the national level, different developments in national food demand were defined on the basis of assumptions for population growth, consumption patterns and export developments (De Koning *et al.*, 1999b). At the sub-national level the protection of nature parks and land use limitations due to land degradation were evaluated with respect to their possible spatial impacts on the land use change dynamics within the country. In contrast to the situation in the Asian case studies, in most scenarios the area agricultural land expanded significantly, resulting in more use of land in existing agricultural areas and frontier-type expansion into areas with rather undisturbed natural vegetation. The patterns of change depended on the increase in demand, competition between land use types, changes in land use drivers, and the area of land that was excluded from agricultural use. Figure 3 indicates the modeled area changes for three land use types in a base-line scenario, taking into account growing demands and stagnating yield developments. In this scenario changes in grassland area are the most widespread, especially through expansion in the Northwest, the Northern Amazon and the Andean footslopes. Areas permanent crops (mostly export crops) also increase. These crops are mainly grown in the lowlands west of the Andes, and to a lesser extent east of the Andes. In the central fertile coastal plains the strongest competition between different forms of land use takes place, especially between permanent crops and temporary (annual) crops.

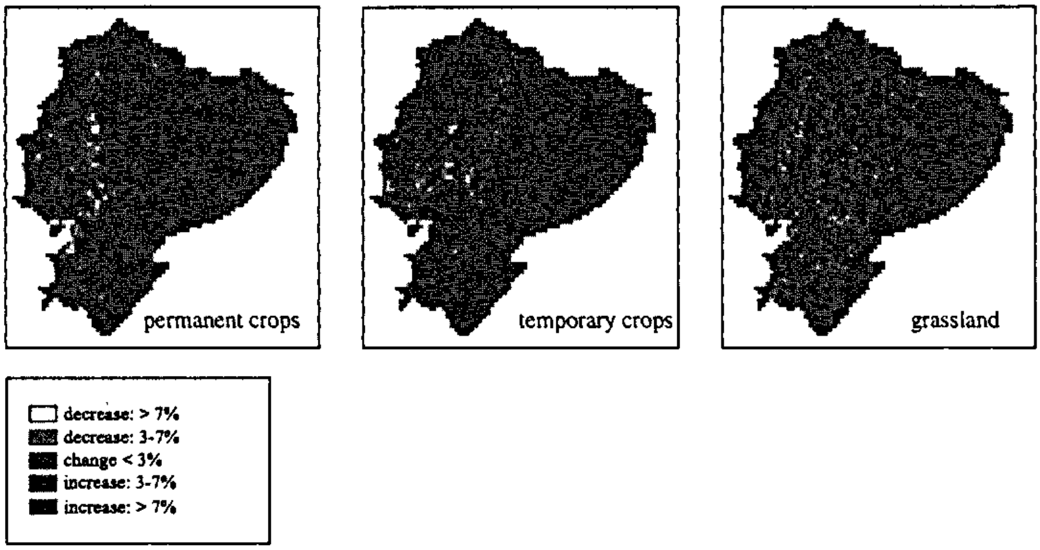

Figure 3: Simulated changes in area percentages permanent crops, temporary crops and grassland in Ecuador over the period 1991-2010 (Source: De Koning et al., 1999b).

Nitrogen balance class	1991		base-line scenario	
	permanent crops	temporary crops	permanent crops	temporary crops
1	25	31	4	14
2	20	25	0	11
3	21	15	21	21
4	34	29	75	54

Table 2. Areas of permanent crops and temporary crops classified according to the annual nitrogen balance. Percentages area in each class are given, the total of the 4 classes sums up to 100%. For 1991 the total area is classified. For the base-line scenario area increases between 1991 and 2010 are classified. class 1: losses smaller than 10 kg/ha; class 2: losses between 10 and 35 kg/ha; class 3: losses between 35 and 60 kg/ha; class 4: losses larger than 60 kg/ha

Possible soil fertility impacts of modelled land use changes in Ecuador were estimated using the NUTMON (NUTrient MONitoring) methodology (Smaling and Fresco, 1993). With NUTMON, nutrient balances of cropping systems are estimated on the basis of the inputs - mineral fertiliser, organic fertiliser, atmospheric deposition, biological N-fixation and sedimentation, and the outputs -harvested product, removed crops residues, leaching, gaseous losses and water erosion. These inputs and outputs are quantified by using a combination of expert knowledge, empirical information and process knowledge. In Table 2 the reported areas of permanent crops and temporary crops in 1991 are classified according to the associated nitrogen balance. The modeled area increases in the base-line scenario are also classified. The results of Table 2 indicate that relatively more of these new areas fall within the classes of the highest nitrogen losses. These results suggest that the best soils are already being used and that expansion into marginal areas depletes resources at a faster rate.

4.4 Modeling results for Sibuyan Island, Philippines

The CLUE model is applied to the island Sibuyan in the province of Romblon, Philippines. The island measures 28 km east to west at its widest point and 24 km north to south, with a land area of approximately 456 km^2 surrounded by deep water. In the center of the island lies a large protected area (Mount Guiting-Guiting Natural Park). It is characterized by its steep mountain slopes, covered with forest canopy. The land surrounding the high mountain slopes gently to the sea and is used for natural and plantation forest and agricultural, mining and urban activities.

The island is believed to be completely covered by forest until the 1940's. From then on the forest has been cleared from the footslopes. Highest on the footslopes are the grassland derived from deforestation, used for pastures. They are regularly burnt to stimulate new grass growth. Rice paddies are common at low-lying land. Most cleared areas are however used for coconut plantation. The island is surrounded by some mangrove forests, sandy beaches and coral reefs (DENR, 1997). See also figure 4A.

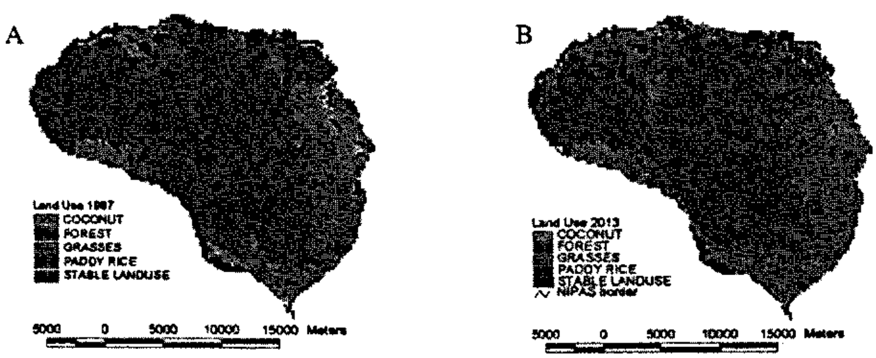

Figure 4: Land use patterns in Sibuyan 1997 (A) and 2013 (B).

The CLUE high resolution model version evaluates a base line scenario for Sibuyan for 15 years (1997-2013). The higher resolutions demand a different data representation and modeling approach. Where the low-resolution data made use of non-homogeneous grid cells, this model version is based on homogeneous grid cells. The scale is 250x250 m.

A statistical analysis based on logistic regression is used to find the most important determinants of the land use patterns. Five to ten driving factors are necessary to explain the four dynamic land use types, coconut, forest, grass and rice. The population density, which acts over large distances, is taken into account by using an upscaling of grid information by a focal function.

The demands that are used are the linear extensions of the development between 1940-1997. The assumption is that the island is first opened up from 1940 on and that a linear development has occurred until 1997.

The model predicts the further development along the footslopes of the mountains especially in the west and the north (figure 4B). Especially the coconut plantations expand towards the northern part of the island. The northwestern part consists of very steep slopes, too steep for coconut, but some patches

of grassland are developing. Some of the rice paddies will move to the southwest, and also more new paddies will develop here.
The black line in figure 4B indicates the NIPAS-area. This is the border of the Mount Guiting-Guiting National Park. Without taking the border into account, the park will slowly be invaded for agricultural purposes, especially on the East Side. However, it also shows that new agricultural developments mainly occur at the West Side of the island.

4.5 Validation

Uncertainties in predicted land use change can arise from both non-realistic scenario conditions and allocation errors. The allocation algorithm of the CLUE model has been validated successfully in a number of cases (de Koning *et al.* 1999a; Verburg *et al.* 1999c; Kok *et al.* 2000). The validations were made through the simulation of historic, documented land use changes. Validations were made at different spatial resolutions in order to learn the ability of the model to precisely allocate land use change as well as its ability to explore the general pattern of change. An example of the results of a historic validation of the model performance is given in Figure 5 (Kok *et al.*, 2000). Any land-use change scenario and model has a high, inherent, uncertainty due to the complexity of the system addressed. Therefore results of land use change models should never be treated as predictions for future land use but rather as exploration of the potential dynamics of the land use system.

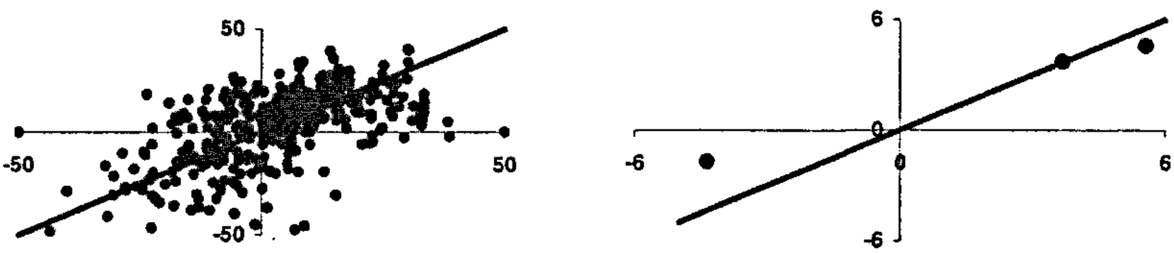

Figure 5: Validation for Honduras at two levels of aggregation: individual grid-cells (left) and agro-ecological zones (right); x-axis observed land use change between 1974 and 1993, y-axis simulated land use change (% change) (Kok *et al.*, 2000)

5. DISCUSSION

Land use change information is essential to assess the effects of human influence on natural resources. Estimates of carbon emission are subject to high degrees of uncertainty, due in large part to difficulties in assessments of land conversion across local to regional scales (Dietz *et al.* 1997; Moran, 2000). It is also a consequence of the fact that terrestrial vegetation and soils are extremely heterogeneous over the land surface, and estimates of the magnitude of carbon emissions during clearing and of carbon gains during regrowth of vegetation vary substantially. Hence, for improved assessments there is a need of spatially explicit assessments of land use change. Similar considerations hold for assessments of changes in nutrient balances, important for sustainability in agricultural production and environmental quality (Smaling *et al.* 1993; de Koning *et al.* 1999b). Other applications that directly use spatially explicit information on land-use change are erosion/sedimentation models and water resource assessments (Wear *et al.* 1998) and biodiversity (Lebel *et al.* 1998; van der Meer *et al.* 1998). Maintaining biological diversity depends on the spatial arrangement of land-uses on the landscape, because of the importance of fragmentation and habitat size on the risks of extinction. The spatial arrangement of land-uses also has implications for ecosystem function, and hence the goods and services. For example, the way in which residual forest is distributed relative to the stream margin can have an impact on soil erosion and hydrology of a catchment. Finally, how natural disturbances like fires, pests and diseases propagate through a heterogeneous landscape clearly depends on its structure. The evaluation of different scenarios based on different policies and development trajectory can help to assess these spatial patterns and their effects on biodiversity, food production and other ecosystem functions (Figure 6). This way spatial modeling can improve land use planning and inform policy making (Farrow *et al.* 2000).

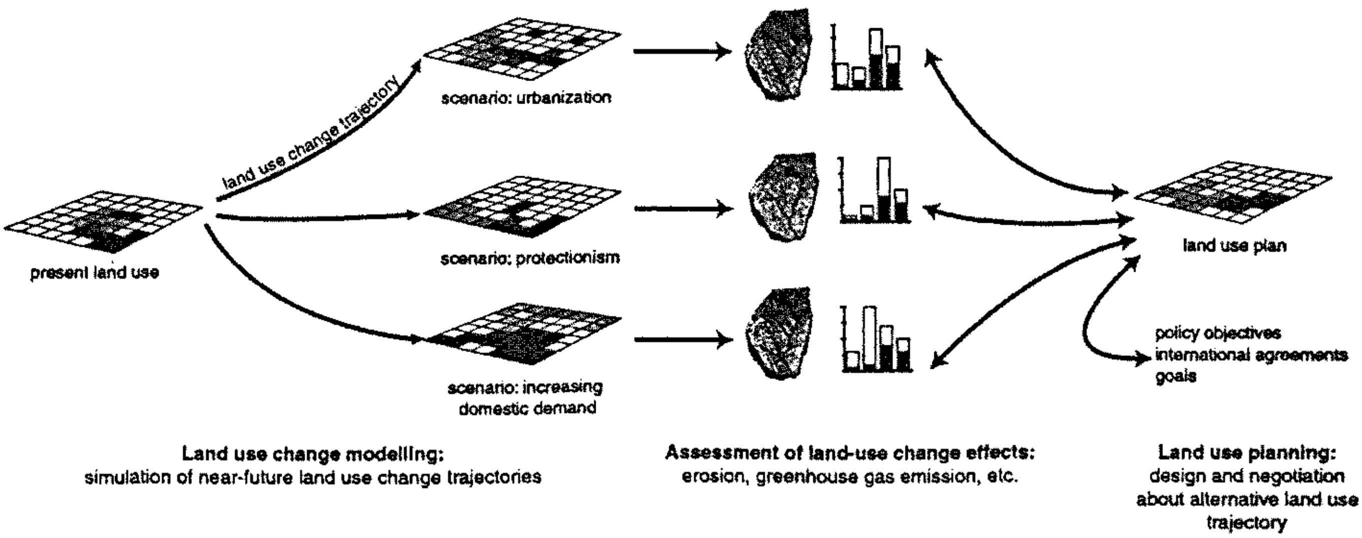

Figure 6: The role of land-use change modeling within studies aiming at improved land use planning

Apart from these biophysical assessments land use change studies can also help to identify vulnerable people and places in the face of global change. Differential impacts and abilities to respond create winners and losers in this change. Whether involving land fragmentation, degradation of agricultural productivity, declines in economic well being, or involuntary human migration, land-use/land-cover change plays an important role. The results of spatially explicit land-use change models allow a straightforward identification of areas that are likely to face high rates of land-use change in the near future, so-called 'hot-spots' of land-use change. Based upon results of the CLUE modeling framework (Verburg *et al.* 2000b) identified regions in China that are lacking behind in economic development while, at the same time, these regions are faced with deteriorating land resources. The identification and understanding of the dynamics underlying these regional differences will help to focus in-depth research and policy intervention at the most threatened regions.

After all intellectual efforts of properly describing land use dynamics and their associated effects the main task scientists are faced with is the communication of their results to the stakeholders. Ideally, stakeholder have been involved during the research itself in 'social learning' processes (Röling *et al.* 1999), which ensures that the appropriate questions are answered. Appropriate presentation of the result is extremely important. Most stakeholders are not eligible to read scientific papers or bulk reports. For the presentation of spatially explicit assessments of land use change the researcher can make use of the visual capabilities of geographical information systems. The presentation of maps to decision-makers is appropriate to communicate results and provoke discussions between policy makers and scientist on the seriousness of the foreseen changes (Goodchild, 2000). Spatially explicit representation of land-use changes has also proven to be an appropriate means to discuss resource bases, spatial interconnectivities between areas and the consequences of local actions with farmers (Gonzalez, 2000).

Integration of disciplines over different spatio-temporal scales is necessary in order to address the issues relevant for actors and stakeholders at different organizational levels in land use and natural resource management. The methodology demonstrated in this paper offers an analysis of land use change dynamics at the landscape level and can supplement land use change studies at the individual actor or community level. The applications of the information generated by the model are large and can help to better manage natural resources in a sustainable manner.

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