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CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica

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Abstract

A dynamic geo-referenced land use/cover model (CLUE-CR) which simulates simultaneous local, regional and national land use/cover changes in Costa Rica is presented and discussed. CLUE-CR simulates the effects of changing demographical and biophysical driving forces on land use/cover change in Costa Rica, including feedbacks from land use/cover to those forces. The multi-scale aspect of the model allows the simulation of realistic system dynamics related to the interaction of top-down and bottom-up effects and constraints. As a model CLUE may be implemented for other countries and has the potential to be scaled down and/or up to link with regional land use models or integrated global change models.

Keywords: Costa Rica; Land use; Cover model

1. Introduction

Realistic land use/cover change models need to integrate different spatial scales and their specific drivers, and should be able to simulate land use/cover changes in response to changes in their biophysical and economic/human drivers (Turner et al., 1993). Feedback relationships in such models should include biophysical-demographic interactions as well. Because such feedbacks also entail effects and drivers at different scales, multi-scale dynamics are essential (Rosswall et al., 1988). Currently, no operational model of land use/cover is available to fulfil all these requirements. At present, our understanding of the links between scales is still poor. Yet, it is well known that changing the scale of the analysis changes the results (Gallopín, 1991; Milne, 1991; Meyer and Turner, 1992; Reed et al., 1993).

Many global and large-scale sub-global analyses identify variants of the so-called PAT variables (population, affluence and technology) as having the strongest statistical correlations with environmental change (Bilsborrow and Okoth-Ogendo, 1992), often implying that the specific variables in questions are the underlying driving forces of change. Local case studies, however, usually do not concur (Clark, 1987; Brouwer and Chadwick, 1991). This result is not clearly understood yet, but may reflect subjectivity brought into studies, or it may reflect problems of aggregation/disaggregation, or it may be related to spatial and/or temporal scale-dependent hierarchies of complex systems (Kolasa and Pickett, 1991; Fresco and Kroonenberg, 1992).

Two examples of operational models which attempt to simulate land use dynamics are the AGE model (Fischer et al., 1988) and the IMAGE 2 model

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(Alcamo et al., 1994). Both models are global models of world food supply and agricultural systems which consist of a number of linked national or world regions. Of these models the IMAGE 2 model is currently the most comprehensive model including a rule-based land cover model (LCM) that is linked to the changing demand for agricultural commodities (Zuidema et al., 1994). In LCM simulations of the human driving forces are derived from scenarios for demographic, economic (GNP), and technological developments which are implemented for 13 world regions (broad aggregated regions). These exogenous forcing functions affect the land use system without accounting for demographic, economic or technological feedbacks in response to simulated scarcities. Most modelling attempts have been successful within their own, often very limited, validity and scale domain but unfortunately they generally exclude other domains. Scale as well as thematic limitations put strong constraints on the application of these models for real world scenarios. As long as no inter-scale dynamics are included in land use/cover change models no realistic simulations will be feasible.

A recent attempt to formulate a framework to model land use/cover dynamics was done within the CLUE (Conversion of Land Use and its Effects) framework (Veldkamp and Fresco, 1996a). In this paper we present and discuss a first dynamic multi-scale land use/cover change model based on the CLUE framework. This model is operationalized for Costa Rica (CLUE-CR) at local, regional and national scales.

1.1. Costa Rica

Costa Rica (Fig. 1) was chosen as a first case study because this country is well known for its great biophysical diversity (Holdridge, 1967; Gómez, 1986), has a rapid expanding population and is relatively well documented. Moreover, Costa Rica is characterized by rapid changes in its land use/cover, especially deforestation (Keogh, 1984; Sader and Joyce, 1988; Veldkamp et al., 1992).

The georeferenced gridded data (0.1° or 6′ *geographical* grid, approximately $7.5 \times 7.5 = 56.25$ km^2 at the Equator) used in this modelling study were derived from the population and agronomic census data for Costa Rican districts (DGEC, 1976a,b,1987a,b), the preliminary atlas of Costa Rica (Nuhn, 1978) and from climate maps (Herrera, 1985).

2. Land use / cover drivers in Costa Rica

Previous research (Veldkamp and Fresco, 1996b) had already extensively investigated to what extent and how the distribution of Costa Rican land

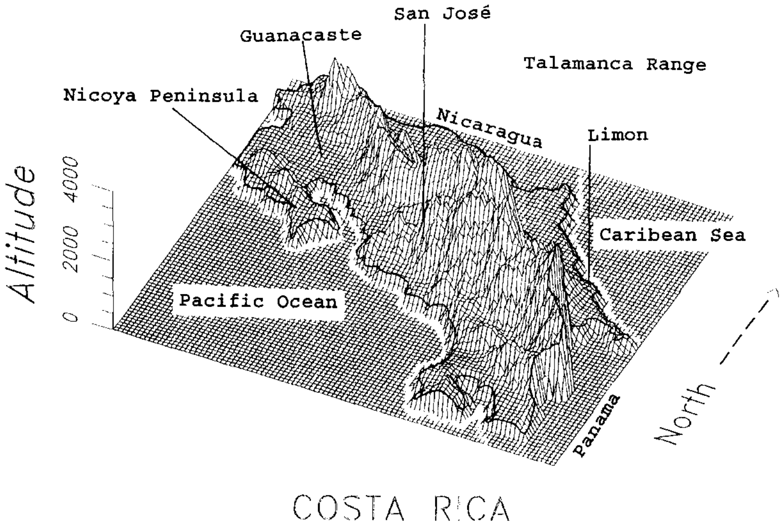


Fig. 1. Costa Rica, some cities and regions.

use/cover and its changes between 1973 and 1984 are related to biophysical and human factors at different spatial scales. Spatial distributions of potential biophysical and human land use/cover drivers or their proxies (altitude and/or temperature, relief, soil drainage, rural population, urban population) were statistically related to the distribution of pastures, arable lands, permanent crops, natural and secondary vegetation, for 0.1° grid units and five artificially aggregated spatial scales. Multiple regression models describing land use/cover variability demonstrate changing model fits and varying independent contributions of biophysical and human factors, indicating a considerable scale dependency of land use/cover patterns in Costa Rica. The observation that for both investigated years each land use/cover type has its own specific scale dependencies, suggests a relatively stable scale-dependent system. In Costa Rica two major land use/cover trends between 1973 and 1984 can be discerned: (1) intensification in the urbanized Central Valley and its surroundings where agriculture in response to a high population density extended to steeper and less favourable soils; (2) land use expansion in remoter areas, where the extension of arable land, permanent crops and pastures increased at the cost of natural vegetation (mainly forest). This deforestation was not related to land shortage.

3. Model description of CLUE-CR

3.1. Model type

The CLUE-CR model was based on the CLUE prototype model (Veldkamp and Fresco, 1996a) with specific additions to allow incorporation of the relationships from the nested scale analysis. CLUE-CR is a discrete finite state model (Ziegler, 1976) written in PASCAL and runs on a VAX-4300 (it takes about 30 s CPU time for a run of approximate 252 time steps (21 yrs)). The model integrates environmental modelling and a geographical information system allowing a classification of CLUE-CR as a cross-disciplinary model (Steyaert, 1993). The model is currently tuned with the results of a nested scale analysis of 1973 and 1984 data.

3.2. Simulated land use / cover types in CLUE-CR

Five different land use/cover classes (in % of total grid cell cover) are simulated. Based on the agricultural census the following aggregated land use/cover classes are used:

Arable land (ARA), comprising of annual crops like maize, beans and rice etc.

Permanent crops (PER), comprising perennial crops like coffee, bananas, palms etc.

Pastures and range lands (PAS), comprising all grass land types (with and without trees) used for grazing cattle.

Natural vegetation (NAT), comprising tropical rainforest to savanna to paramo (alpine vegetation).

Residual group (RES) comprising the remaining land uses and covers like secondary vegetation, towns, roads, bare rock etc.

3.3. Overall assumptions in CLUE-CR

The following overall assumptions were used in CLUE-CR:

1. A dynamic equilibrium between the total population and the agricultural production is assumed. This assumption does not rule out trade, but assumes a relatively minor role of this factor.
2. Agriculture is the main employment and income generator in the rural areas of Costa Rica.
3. A grid-cell is the smallest unit of analysis (resolution). Despite its assumed biophysical and demographical uniformity, each grid cell may contain five different land uses/covers.
4. Land use changes occur only when biophysical and human demands can not be met any more through existing land uses.
5. The total land cover consists of five different categories (ARA, PER, PAS, NAT, RES) only, their sum in each grid always being 100%.
6. By incorporating reserves (food and/or money) for two years, seasonal and annual yield fluctuations have no direct effect on the land use changes.

3.4. Model inputs

For *each grid cell* CLUE-CR requires the following data: altitude (m) and/or temperature (°C), relief

Table 1
Schematic description of the CLUE-CR procedures

Procedure	Description
CRNEED	Determines the extension and the demand for the five land covers at the *national* level.
CHANGE	If expansion of certain land covers are required, the CHANGE procedure determines at a *regional* level of aggregated grids were those new covers are most easily allocated. The actual land use conversions/changes take place at the *local* grid level within the selected region.
AUTODEV	The autonomous land use changes (independent of national demands) are simulated by this procedure for each *local* grid cell.
BIOPHEED	This optional procedure allows *local* and *regional* feedback effects of biophysical limitations of certain covers on their yields and local rural/urban population. Examples are effects of erosion, soil fertility, water logging etc.
DISPEST	This procedure allows *local* and *regional* feedback effects of diseases and pests on cover yields and its indirect effects on the local rural/urban population.

(slope), soil drainage (depth groundwater), rural population (no. of people/km^2), urban population (no. of people/km^2), % permanent crop cover, % arable land cover, % pastures and range land cover, % natural vegetation cover, % residual group cover, change rate of rural population, change rate urban population. In the POPGROWTH procedure the population changes are generated during the simulations. As initial condition the Costa Rica data for 1973 are used.

3.5. Schematic overview of modelling sequence in CLUE

CLUE-CR has several different procedures (Table 1) each taking care of different aspects of the dynamic interaction of land use/cover and its drivers. The land use update takes place each year following the following PROCEDURE sequence (see Fig. 2):

3.5.1. CRNEED

CRNEED determines at the *national* level the total rural and urban population, and the total area of the four food/money producing land use/cover classes (ARA, PAS, PER and NAT). The cover 'yields' are assumed to be a function of their extension, local biophysical conditions, technology level, management level and their general intrinsic cover value.

Biophysical conditions determine cover yields with yield reductions related to steep slopes, high altitudes and poor soil drainage. Furthermore, a ran-

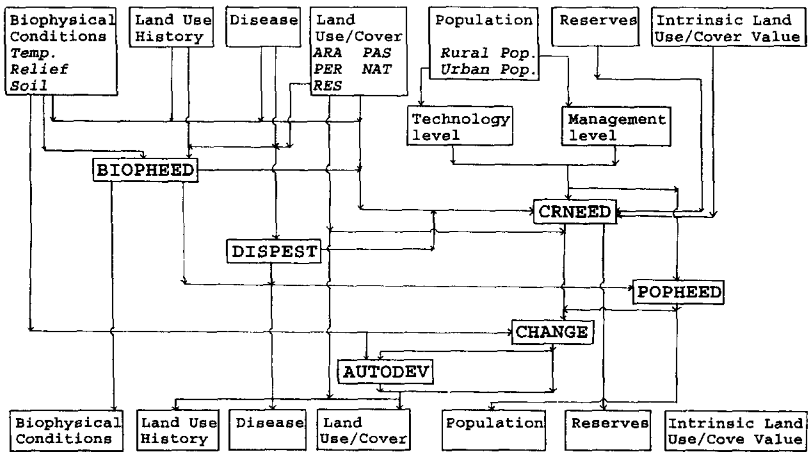


Fig. 2. Flow chart of the CLUE-CR model.

dom annual fluctuation in cover yields is introduced to simulate temporal changes in biophysical conditions (climate). These changes range between −60% and +40% of the mean annual yield level. *Technology level* is simulated as a function of the urban population. In areas near urban centres with a large urban population, the technology level is assumed to be higher. This assumption is supported by the observation that fertilizer and other technological inputs are generally higher in more urbanized areas (DGEC, 1976a,1987a). *Management level* is simulated as a function of rural population. Within CLUE-CR areas with a large rural population are assumed to have a higher management level. This is supported by the high correlation between the rural population, agricultural labour force and crop yields for rural areas (DGEC, 1976b,1987b). The *intrinsic cover value* is a dimensionless value which can be seen as an indicator of the different cover values. The used values in the two presented scenarios (PER = 5; PAS = 3; ARA = 3; NAT = 2) are kept constant but could be made dynamic by linkages with an economic model incorporating market conditions (effects of demand and supply).

The total land use need of the Costa Rican population is thus determined as a function of the total rural and urban population. This need is compared with the yields of the available land use/covers. If the demand and supply of agricultural products do not sufficiently match, the additional requirements for the five land use/cover classes are determined.

3.5.2. CHANGE

As a result of land use/cover requirements at the national level the CHANGE procedure is used to allocate new needed land covers. The nested scale analysis (Veldkamp and Fresco, 1996b) demonstrated that each land use/cover regression model has a maximum scale-dependent model fit. By calculating linear regression models for each use/cover group at six different spatial scales of aggregated 0.1° grids the model fits (coefficients of determination) can be observed to change systematically with scale. The scales with maximum model fit were selected as optimum scale. For each land use/cover class this 'optimum' scale (of aggregated 0.1° grids) is used to select regions (windows) of aggregated 0.1° grids within the country where the required covers are most easily allocated. These optimum *regional scales* are respectively: ARA: 5 × 5 grids; PER: 4 × 4 grids; PAS: 5 × 5 grids; NAT: 6 × 6 grids. The regional selection is done by calculating cover extensions with the scale-dependent regression models which are then compared with the actual regional situation for the desired land use/cover class. When the observed differences allow room to allocate the desired covers, this region is selected. Within a selected region each individual 0.1° grid is evaluated using regression models valid for this *local scale* to calculate the possible changes in land cover. During this evaluation all four calculated land use/cover classes (ARA, PER, PAS and NAT) are taken into account simultaneously. The remaining residual group is simply 100% (grid cover) minus the sum of the calculated four land use/cover classes.

3.5.3. AUTODEV

If no national demand for new covers exists and for those grids which are not selected in the CHANGE procedure, often due to their local or regional conditions or spatial setting, the autonomous land use/cover development is simulated at the *local* 0.1° grid scale in the AUTODEV procedure. The local grid use/cover is evaluated and changed exclusively based on the local biophysical and demographical grid conditions, i.e. independent of the regional and national demands and surpluses. Thus land use/cover in one local grid may change as a result of local characteristics only. The subsequent time step the aggregated effects of all these local grid changes feed back into the regional and national procedures like CRNEED and CHANGE and as such they have a bottom-up effect on the regional and national scales.

3.5.4. BIOPHEED

This optional procedure simulates feedback effects of agricultural over-use or unsuitable use in sensitive areas (grids). Certain biophysical conditions are simulated to have feedbacks as yield reductions. Examples used in scenario 2 are arable lands and permanent crops in steep areas which are more prone to erosion causing a decline in yields (Hall and Hall, 1993), or remote areas with less favourable soils which have a decrease in soil fertility after prolonged use as arable land causing yield reductions (Juo and

Lal, 1977; Dalal and Mayer, 1986). In turn large yield reductions may affect the regional self-sufficiency capacity of areas triggering a migration of the rural population to large urban centres. Several scenario options can be defined and used within this procedure.

3.5.5. DISPEST

The optional DISPEST procedure allows to simulate the spatial and temporal effects and impacts of pests and diseases on the land use/cover dynamics. Since pests and diseases may have catastrophic impacts (Zadoks, 1971), both biophysical and human feedbacks are taken into account. If large areas have strong yield reductions due to pests or diseases, the rural population may also respond by migration to urban centres or other rural areas. More specific characteristics of the disease dynamics as simulated are explained in the description of scenario 2.

3.6. Model drivers

Two different land use/cover drivers operate within the model:
1. Changes in population (urban and rural) which are simulated both as input (POPGROWTH) and as feedback effect of land use/covers.
2. Changes in biophysical conditions which are simulated both as input (initial conditions and disease scenario in DISPEST) and as feedback effect due to current and past land use (BIOPHEED).

3.7. Model scales

The land use/cover evaluations and selections take place at three different levels, national (933 aggregated 0.1° grids), regional units of 16 to 36 aggregated 0.1° grids, and the local individual grid level. More detailed scales are not possible due to the limited data resolution of the data available.

3.8. Model outputs

The model output consists of a GIS (of 0.1° grids) with a georeferenced account of Costa Rican land use/covers (ARA, PER, PAS, NAT, RES), population (rural and urban) and biophysical limitations (relative yield reduction factor) for each selected time interval (between 1 year and the duration of the simulation in years). The same data are also aggregated for the three main biophysical regions/zones of Costa Rica (Fig. 3):
1. The hot and humid region, comprising the Atlantic zone (northeast) and Osa, Golfito (south).
2. The hot and dry region, comprising the coastal Pacific zone.
3. The cool and humid region, comprising the Central Valley and the surrounding mountain ranges.

The data are also aggregated for the national scale of Costa Rica making the outputs available for three different scale levels: *national*, *regional* (3 biophysical regions) and *local* (913 grids as maps).

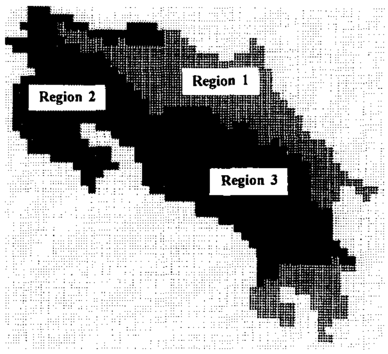


Fig. 3. The three selected agro-ecological regions in Costa Rica. Region 1: hot and humid; region 2: hot and dry; region 3: cool and humid.

4. Two simulation examples

Two different contrasting scenarios of CLUE-CR will be discussed to demonstrate applications and limitations of the model. First a simulation (scenario 1) is presented which represents an extrapolation of the (1973 to 1984) land use/cover system as described by the nested scale analysis (Veldkamp and Fresco, 1996b). The second simulation (scenario 2) demonstrates a simulation of the same land use/cover system but now including biophysical and demographic feedbacks related to erosion and soil fertility and a disease outbreak. Both simulations start with the 1973 data set and simulate possible effects/responses of land use/cover during 21 years.

4.1. Scenario 1

Scenario 1 simulates (21 years) the Costa Rican land use/cover system as described with data from 1973 and 1984. No biophysical and demographic feedback mechanisms are effective and no changes in external conditions/assumptions are incorporated. This scenario is a business as usual situation which is extrapolated in time using linear regression relationships only. The used input, population growth, is a linear extrapolation of the measured population changes between 1973 and 1984.

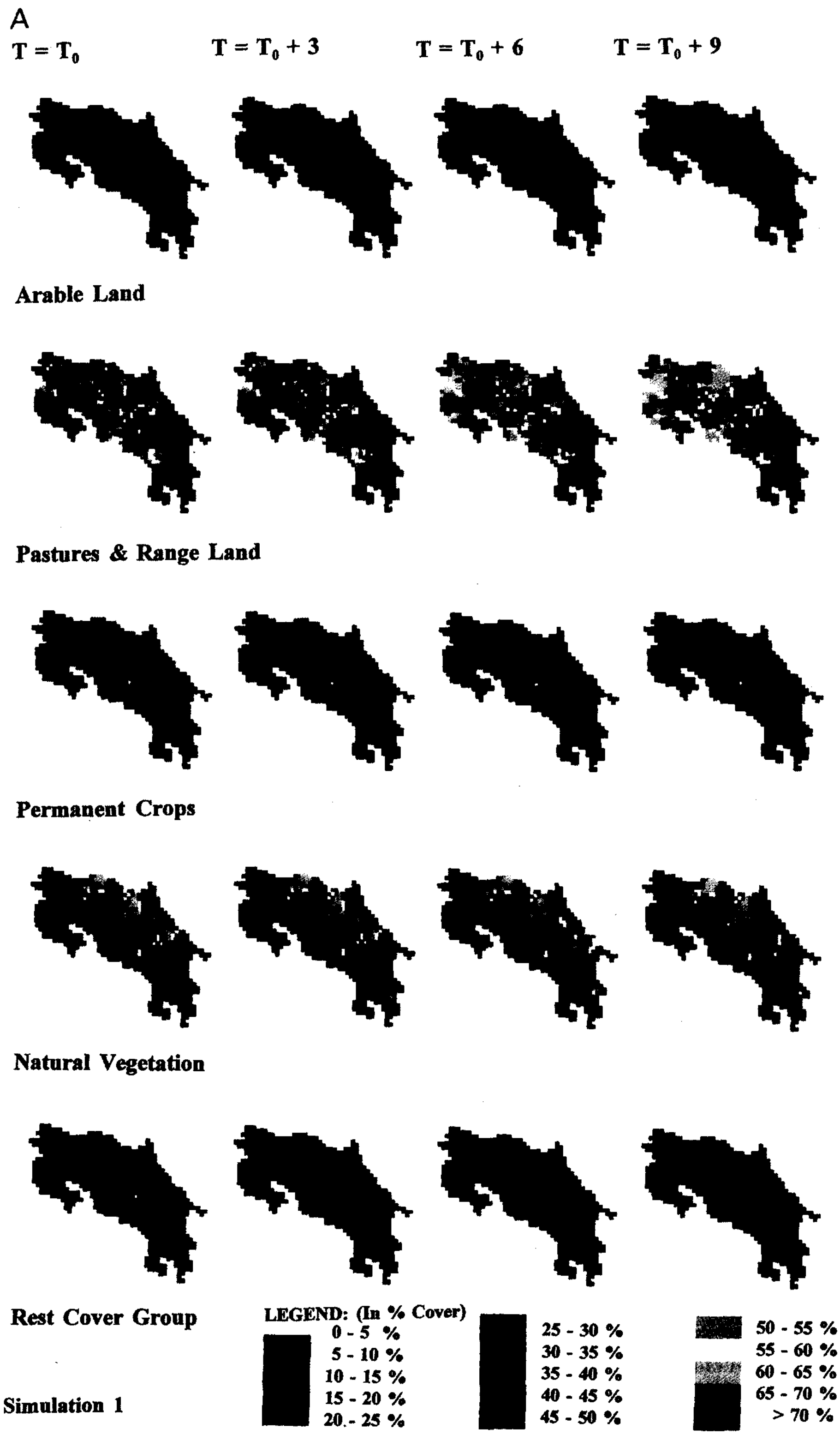
In Fig. 4, the changing five land covers are given in 3-year intervals. The arable land distribution shows hardly any change during the simulation. The pastures and range land show a major decrease in the western Pacific region (Guanacaste) and a slight increase in local areas in the eastern Atlantic region (near Limon). The permanent crops demonstrate a general increase during the simulation throughout the country, with only a minor decrease in some local grids. The natural vegetation continues to decline outside the national parks which can be easily identified as the remaining dark green units at the end of the simulation. The residual cover group (RES) has values of less than 30% of the total grid cover. Some high values are only found at the most southern part of the Nicoya Peninsula.

The five cover classes were also aggregated into the three biophysical regions of Fig. 3 and Costa Rica (Fig. 5). Region 1 (hot and humid) has a general increasing permanent crop cover, a constant arable land cover and decreasing pastures, natural vegetation and residual covers. Region 2 (hot and dry) has increasing permanent crop and natural vegetation covers, a constant arable land cover and a decreasing pastures and residual cover. Region 3 (cool and humid) has an increasing permanent crop cover, a constant arable land cover and decreasing natural vegetation, pastures and residual covers. When aggregated to national level these data demonstrate a national increase in permanent crops, a constant arable land cover and decreasing natural vegetation, pastures and residual covers. The simulation seems to capture rather well the general land use trends as described in literature for the seventies and eighties (Sader and Joyce, 1988; Lutz and Daly, 1991; Veldkamp and Fresco, 1996b). The general decline in natural vegetation (forest) in scenario 1 fits the general deforestation trend, but it was not expected that the central valley and surrounding mountains (region 3) would show a regional increase in natural vegetation.

4.2. Scenario 2

Scenario 2 simulates (also for 21 years and starting in 1973) the Costa Rican land use/cover system including both biophysical and demographic feedback mechanisms related to land use effects (erosion and soil fertility) and the outbreak of an unspecified disease within the permanent crops below the 300 m. The biophysical feedbacks are erosion on arable lands and under permanent crops in steep areas (Hall and Hall, 1993) and decreasing soil fertility in remote areas with prolonged use as arable land (Reiners et al., 1994). An imaginary disease in permanent crops below 300 m is set to start after 5 years of simulation, ten years later a cure or controlling measurements for this disease are introduced (Anderson and Mistretta, 1982). The disease is assumed to start at Limon harbour in the Atlantic Zone and follows a contamination pattern common for banana or cacao diseases with insect vectors (Chan and Jeger, 1994). Like in scenario 1 no changes in external conditions/assumptions are incorporated and the population input is a linear extrapolation of the measured population changes between 1973 and 1984.

In Fig. 6 the changes of the five land covers are given at 3-year intervals. The arable land distribution shows more changes than during the scenario 1 simulation. Several grids within the Atlantic region show an increase in arable land cover while other regions have some decreases as well. The pastures and range lands show, like in scenario 1, a major decrease in the northwestern Pacific region. No area with pasture increase can be observed. The permanent crops demonstrate a general increase throughout the country but less spectacular than in scenario 1. Some local decreases in permanent crops are found in the Atlantic area as may be expected in an area with a permanent crop disease. The natural vegetation has both decline as growth during scenario 2. Most decrease is found in the Atlantic region while the other regions generally display an increase, especially west of the Talamanca range, where a consid-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Arable Land
Pastures & Range Land
Permanent Crops
Natural Vegetation
Rest Cover Group
Simulation 1
LEGEND: (In % Cover)
0 - 5 %
5 - 10 %
10 - 15 %
15 - 20 %
20.- 25 %
25 - 30 %
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35 - 40 %
40 - 45 %
45 - 50 %
50 - 55 %
55 - 60 %
60 - 65 %
65 - 70 %
> 70 %

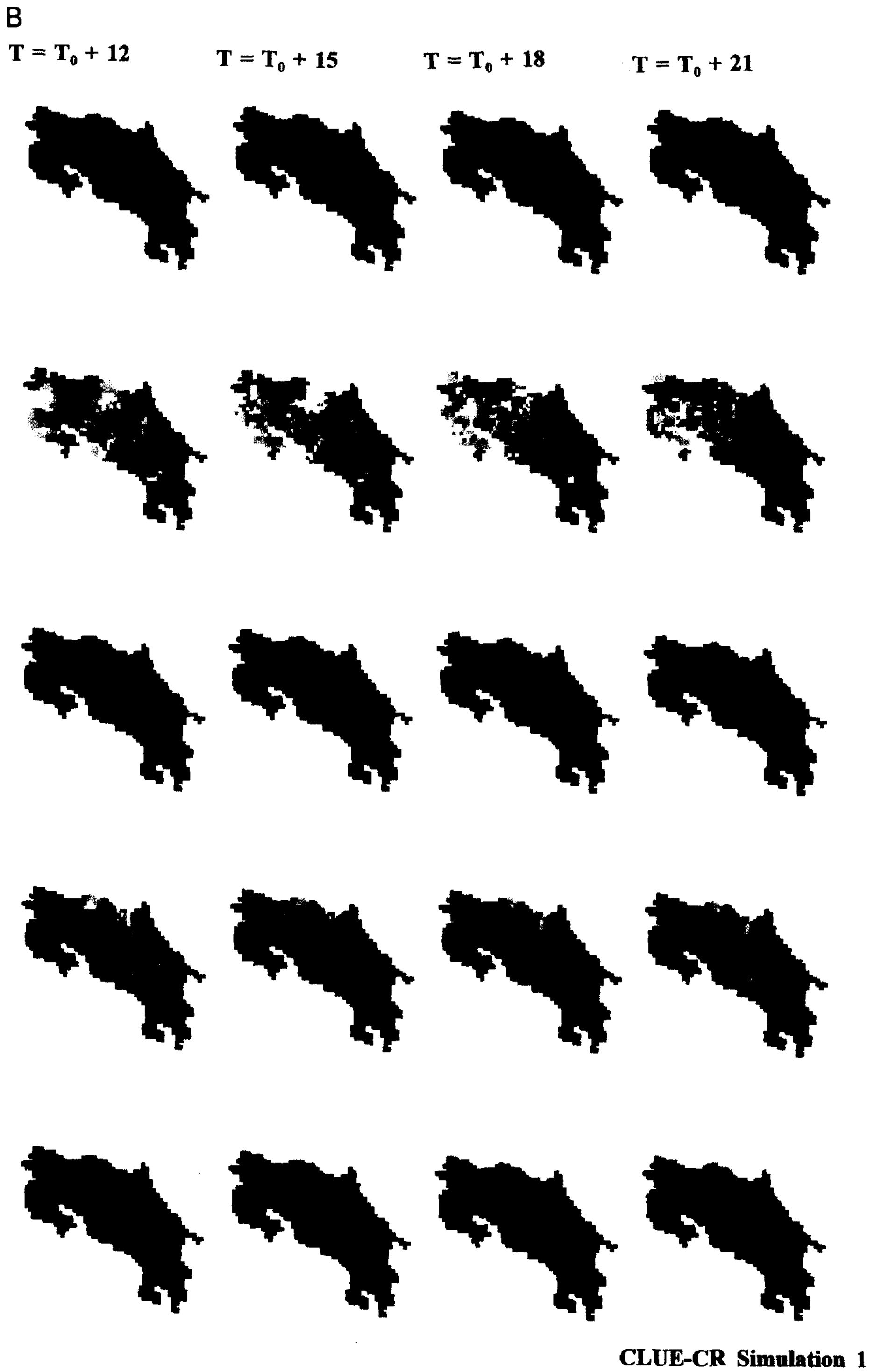


Fig. 4. Scenario 1 simulation of land use/cover distributions of permanent crops, pastures, arable land, natural vegetation and residual cover during 21 years in 3-year intervals. The initial condition represents 1973.

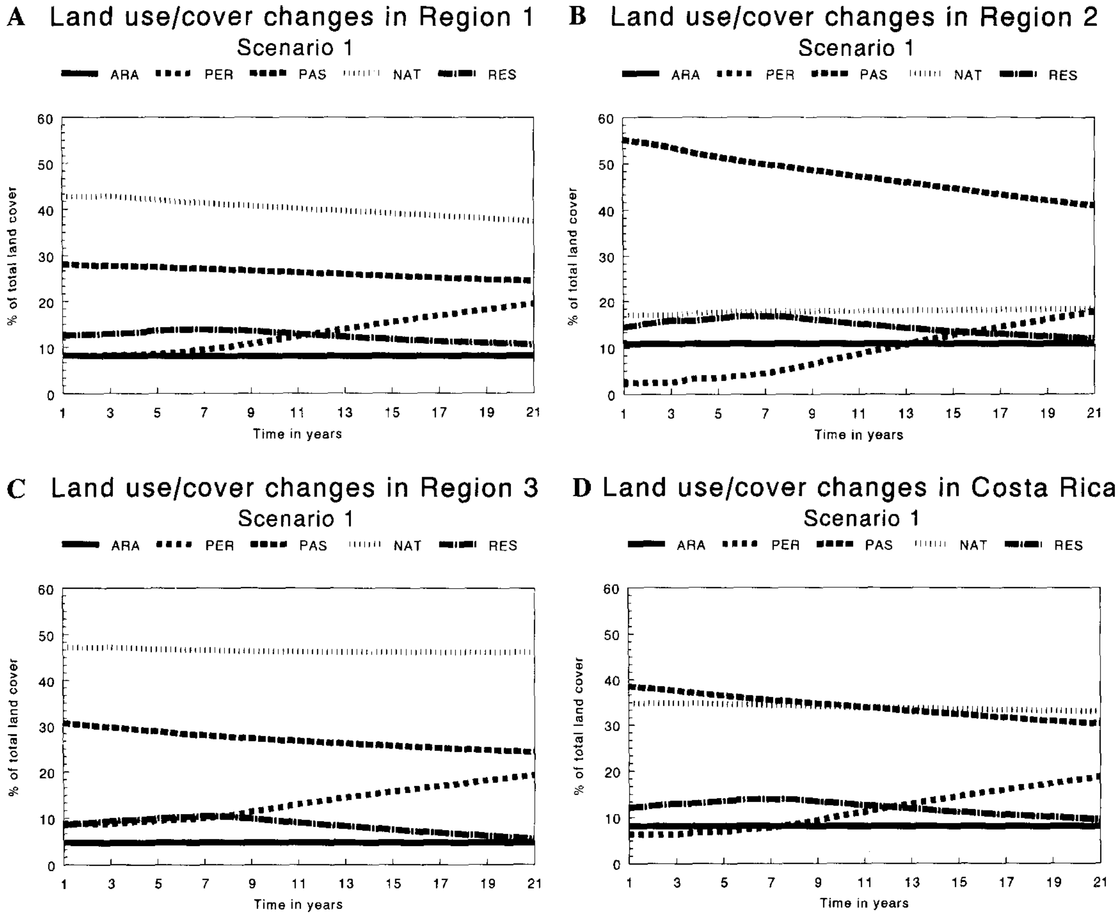


Fig. 5. The changes in covers during the simulation of scenario 1 of permanent crops, pastures, arable land, natural vegetation and residual covers (in % total cover) aggregated to the three regions of Fig. 3 and Costa Rica.

erable region with expanding natural vegetation can be observed. Like in scenario 1 the residual cover group has only some high values at the most southern part of the Nicoya Peninsula. As the majority of the residual covers is below 30% of the total grid covers these few grids with high residual covers are probably a model artefact caused by boundary effects.

The five cover classes were also aggregated for the three biophysical regions and Costa Rica (Fig. 7). Region 1 (hot and humid) has both an increase and a decrease in permanent crops a general increase in arable land and residual cover and a decrease in pastures and natural vegetation. Region 2 (hot and dry) has increasing permanent crop, natural vegetation and residual covers, a slightly decreasing arable land cover and a more strongly decreasing pastures. Region 3 (cool and humid) has an increasing natural vegetation and residual cover, an almost constant permanent crop cover and decreasing arable lands and pastures. Aggregated to national level these data demonstrate a slight increase in permanent crops and natural vegetation and residual covers and decreasing trends for pastures and arable lands.

Again the different aggregation scales demonstrate grid and region-specific land use dynamics. The differences between the two scenarios are quite clear. The biophysical feedbacks cause the abandoning of unfavourable grids near the central valley and its surroundings. The outbreak of a disease in the humid low lands caused a considerable decrease in permanent crop growth in Region 1. The observed delay in response to the simulated disease outbreak and its recovery is caused by the assumed slow impact of crop contamination as simulated by a disease spreading model of Chan and Jeger (1994). Both biophysical and disease feedback effects cause local and regional disequilibrium between rural population and land uses/covers, stimulating a local decrease in rural population and an increase in urban population, changing the national demands and related allocation patterns. The incorporation of biophysical and demographic feedback effects caused considerable changes in the simulated land use/cover trends. Instead of a decrease in natural vegetation in scenario 1 a national increase can be observed in scenario 2. The strong increase in permanent crops in scenario 1 is strongly reduced in scenario 2. The almost constant arable land cover in scenario 1 is changed into a decreasing trend in scenario 2. These reversed national trends can also be observed for the three regions. Furthermore, it is also demonstrated that all regions and grids can influence one another directly or indirectly. The introduction of a permanent crop disease within the lower areas (< 300 m) has also clear effects on the permanent crop cover dynamics within the higher areas of region 3 (Fig. 7).

5. General discussion

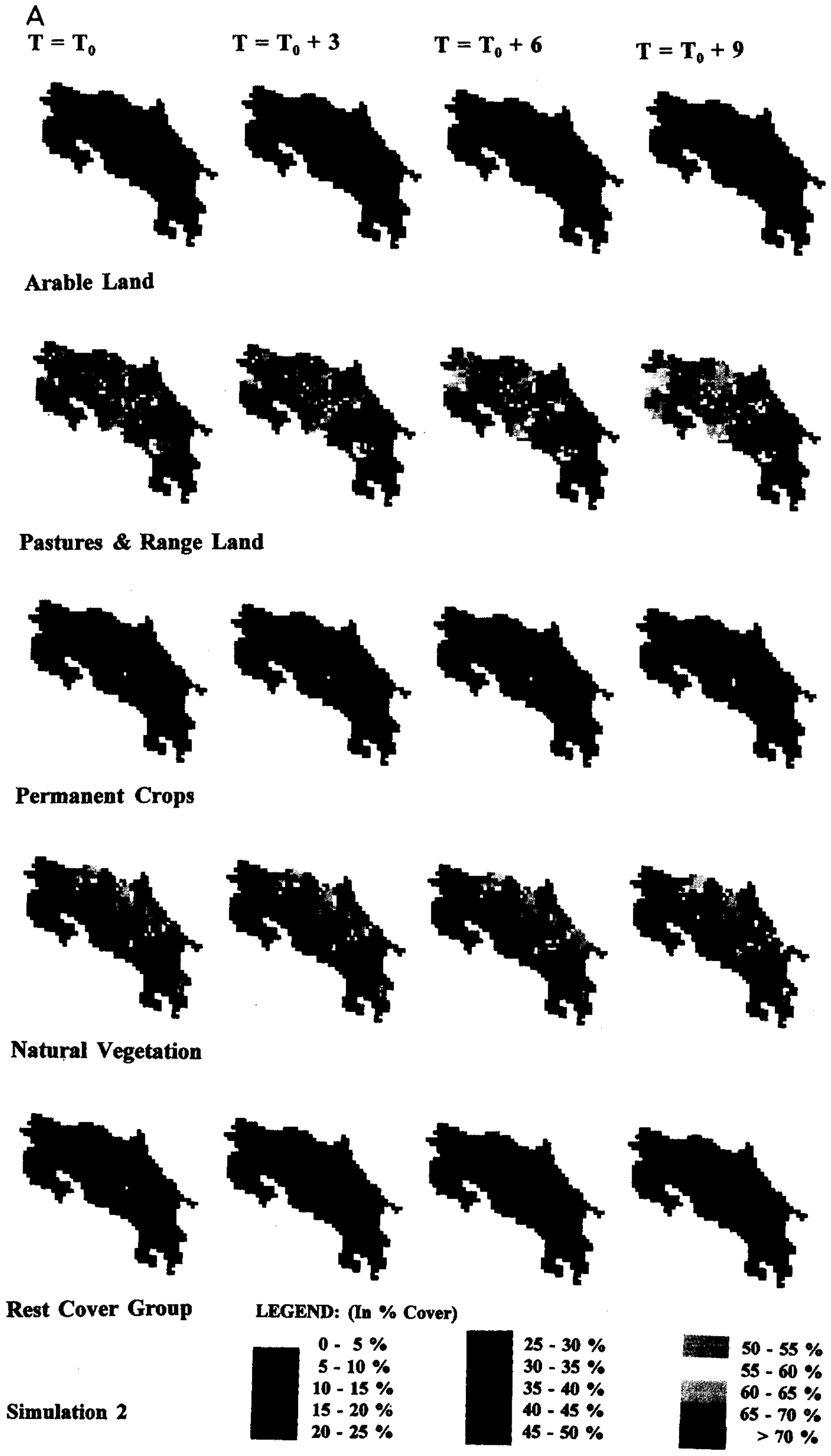
Overall model performance indicates that despite the use of data of two years only we were able to capture the essential land use/cover dynamics of Costa Rica during the 1973–1984 period in CLUE-CR as shown by other, independent research (Sader and Joyce, 1988; Lutz and Daly, 1991). The use of only two years has as major disadvantage that we could only use linear relationships to extrapolate the observed land use/cover dynamics. Although we only used linear regressions their combination (5 cover classes at 6 scales) does not always result in linear effects (see also Fig. 5 and Fig. 7). Still, combined use of linear relationships will never lead to abrupt non-linear changes.

When the data of the 1995 census data will become available in the nearby future we expect to be able to simulate Costa Rican land use dynamics more realistically. For the time being we can use CLUE-CR as a tool to gain more insight in Costa Rica land use development by formulating plausible scenarios. In our scenario 2 we demonstrated the possible effects of a realistic disease scenario incorporating the effects of both biophysical as well demographic responses. Without more data to allow a more accurate calibration CLUE-CR has no direct predicting value of the land use/cover system. Other aspects of the model which can and need to be improved are the absence of economic feedbacks and the use of linear model relations and population change inputs. Despite all these imperfections the current model demonstrates the relevance of multi-scale and inter-scale dynamics within land use/cover systems. By describing and incorporating different scale levels (at least three; Odum, 1983) of the land use/cover system we were able to simulate both top-down as well as bottom-up effects and their interactions. These scale interactions seem to extinguish extreme system deviations within the model simulations. This stabilizing scale effect is mainly due to the fact that the all system scales are interrelated causing the system to respond as one entity, independent of the scale of input. It can therefore be expected that multi-scale system descriptions and model calibrations will contribute to better/realistic model simulations of the complex land use/cover system.

5.1. Model tuning and sensitivity

As with most simulation models desired outputs can be obtained by an extensive tuning exercise. In CLUE-CR such a specific tuning step was not necessary because we used the outcome of the nested scale analysis, a set of 6×5 scale-dependent land use/cover linear regressions as model input. These relationships were obtained by a standard methodology (Veldkamp and Fresco, 1996b) which can always be reproduced, a characteristic not valid for a tuning exercise.

To gain some insight in the model performance a first tentative estimate of simulation errors was established by comparing the simulated results with the 1984 data. This exercise has some merit because the 1984 data were not used directly within the calibration phase. We only used the statistical description of the land use system which is only partly based on the 1984 data.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Arable Land
Pastures & Range Land
Permanent Crops
Natural Vegetation
Rest Cover Group
Simulation 2
LEGEND: (In % Cover)
0 - 5 %
5 - 10 %
10 - 15 %
15 - 20 %
20 - 25 %
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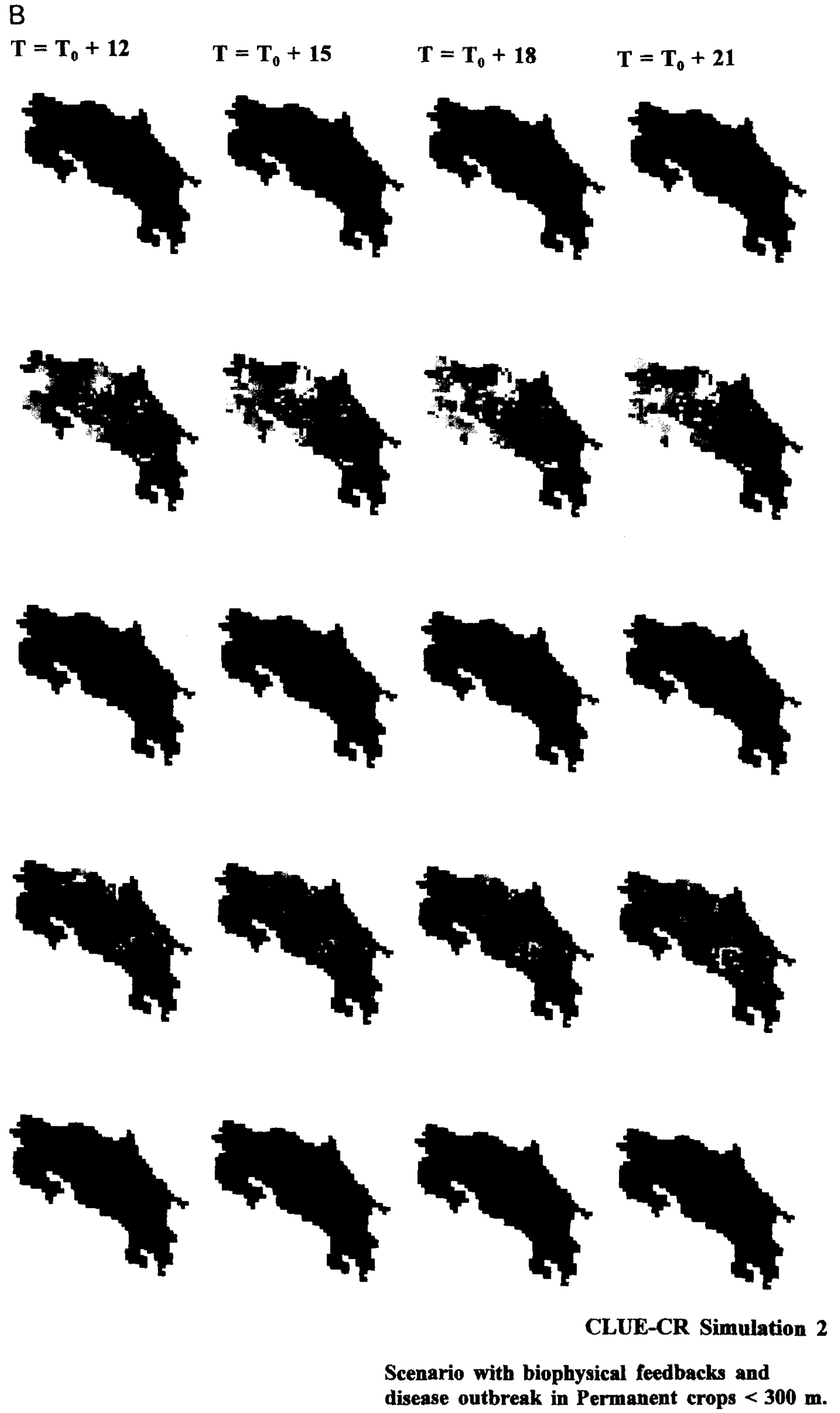

Fig. 6. Scenario 2 simulation of land use/cover distributions of permanent crops, pastures, arable land, natural vegetation and residual cover during 21 years in 3-year intervals. The initial condition represents 1973.

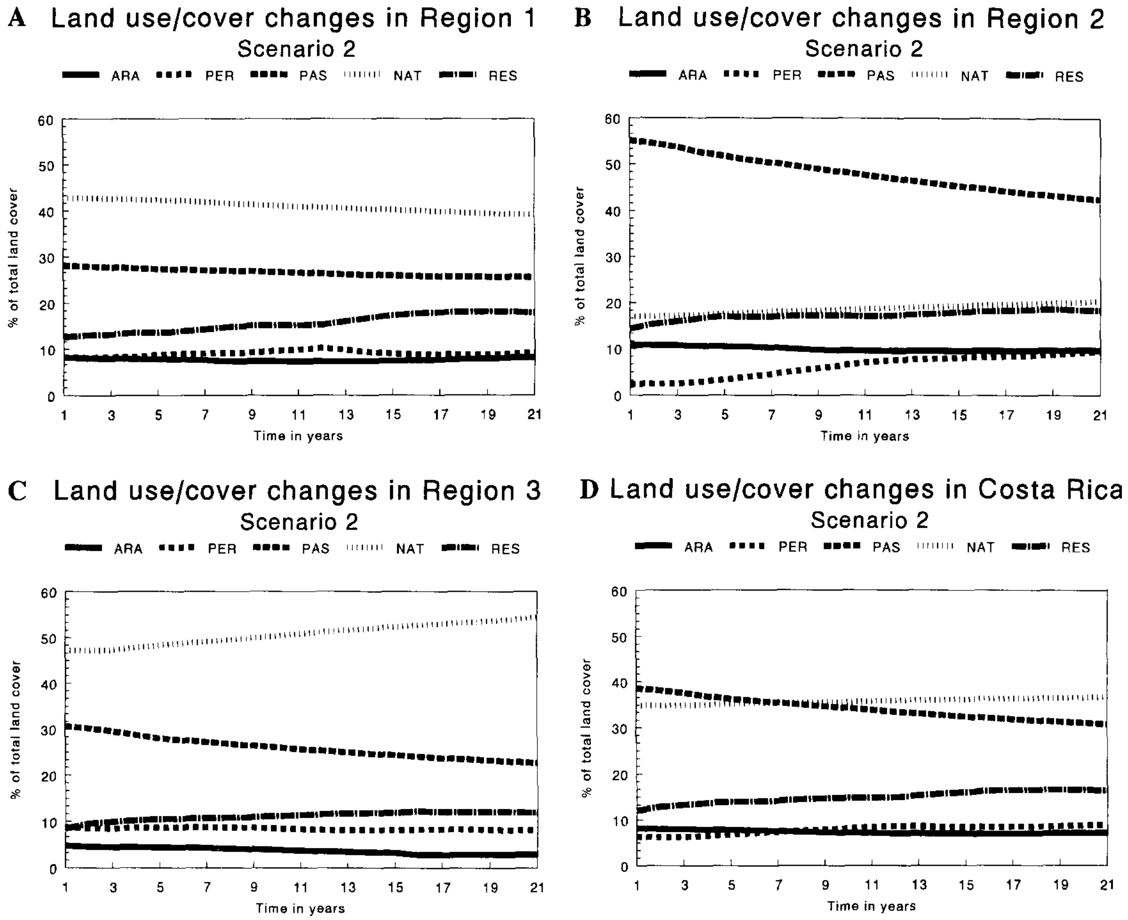

Fig. 7. The changes in covers during the simulation of scenario 1 of permanent crops, pastures, arable land, natural vegetation and residual covers (in % total cover) aggregated to the three regions of Fig. 3 and Costa Rica.

To highlight the differences between the simulation results and the 1984 data the *absolute differences* between the two were calculated for the three biophysical regions and Costa Rica as a whole (Table 2). In reality the differences between the scenario covers and the 1984 cover data are less pronounced as suggested by the absolute differences due to compensating accounting effects. After 11 yrs of simulation the differences between the two scenarios are not very pronounced because the impact of the disease in scenario 2 is not yet at its maximum. Still the business as usual scenario (1) has fewer maximum differences from the 1984 data than scenario 2. The maximum absolute deviation of 21.7% of total land cover seems given all data limitations reasonable. Region 3 has the lowest maximum difference, suggesting that CLUE-CR simulations are somewhat better for the central valley and its surroundings than the other two regions. To gain insight in the contributions of the different covers to the total differences their relative contribution to the measured absolute differences are given in Fig. 8. It is obvious from this bar chart that the each region has its specific cover contributions to the observed maximum differences. Furthermore, the relative contributions seem scenario-dependent. These very preliminary model sensitivity estimates indicate that our modelling approach appears robust and specific enough to describe the general multi-scale dynamics of land use/cover system.

5.2. CLUE-CR *applications*

With additional and better temporal resolution data, the model performance of CLUE-CR can be much improved. Should this be achieved CLUE-CR may be applied as a policy supporting instrument. For the moment CLUE-CR can only be used to demonstrate possible and plausible responses to certain policies of the land use/cover system at *national* and *regional* scales. CLUE-CR can be improved along two different research lines: model extension to more detailed scales or to more aggregated scales. Application to more detailed scales requires high resolution data (both spatial and temporal), while application to more aggregated scales requires data of similar resolution as in the current model version, but for much larger areas, thus making a model extension outside Costa Rica necessary.

If more detailed regional assessments are required the common land use planning methodologies based on land evaluation and farming systems analysis (Fresco et al., 1994) are presently more suitable. The most integrated application would be a combination of regional land use planning combined with CLUE-CR simulations. First, CLUE-CR can be used to determine the expected regional developments (for the three biophysical regions) from selected scenarios. Subsequently, these simulated conditions and trends should be regionalized applying aerial photographs or satellite images (Huising, 1993) and farm or household research (Kruseman et al., 1994). This combined knowledge is then to be evaluated in an integrated land use planning model like the USTED model for the Atlantic Zone (Alfaro et al., 1994). The calculated land use options which are identified as most promising can then be fed back into CLUE-CR to check to what extent they influence regional of national land use/cover systems. The model would gain by linking with a multi-scale economic model. If economic feedbacks could be incorporated in CLUE-CR, a link with regional land use planning models (like USTED) using multi goal linear programming MGLP with economic parameters would be much easier.

CLUE-CR may form a tool to assess the effects and impacts of climate change on Costa Rica land use dynamics. Given the considerable uncertainties of CLUE-CR simulations and the fact that General Circulation Models (GCMs) simulations predict relative small climate changes for Costa Rica (Houghton et al., 1990) which are all well within the observed data range of the past decades (Brenes and Saborio Trejos, 1994), direct assessments of climate change impacts on Costa Rican land use system seem inappropriate. Such assessments will be only relevant when carried out from a global perspective as at-

Table 2
Differences (in % region cover) between 1984 data and scenario 1 and 2

Cover type:	PER	PAS	ARA	NAT	RES	Total
Absolute difference (in % total region cover) between 1984 data and scenario 1						
Region 1	5.3	11.4	1.9	7.1	0.9	26.6
Region 2	4.7	7.9	3.8	5.3	1.7	23.3
Region 3	2.2	4.7	2.1	3.3	1.3	13.6
Costa Rica	4.2	8.3	2.6	5.4	1.3	**21.7**
Absolute difference (in % total region cover) between 1984 data and scenario 2						
Region 1	2.8	11.2	2.6	7.8	3.2	27.7
Region 2	3.1	7.5	5.1	6.0	3.6	25.2
Region 3	2.5	5.9	3.1	7.9	3.6	23.0
Costa Rica	1.4	8.4	3.7	7.2	3.4	**24.1**

tempted in IMAGE 2.0 (Alcamo et al., 1994). However, CLUE-CR extensions to global scales, seem only feasible when CLUE-CR is linked to existing global scale models like IMAGE 2.0. Since IMAGE 2.0 uses world-regions where Central and South America comprise one unit, considerable upscaling of CLUE-CR is required. This upscaling can be attempted by establishing links with neighbouring Central Ameri-

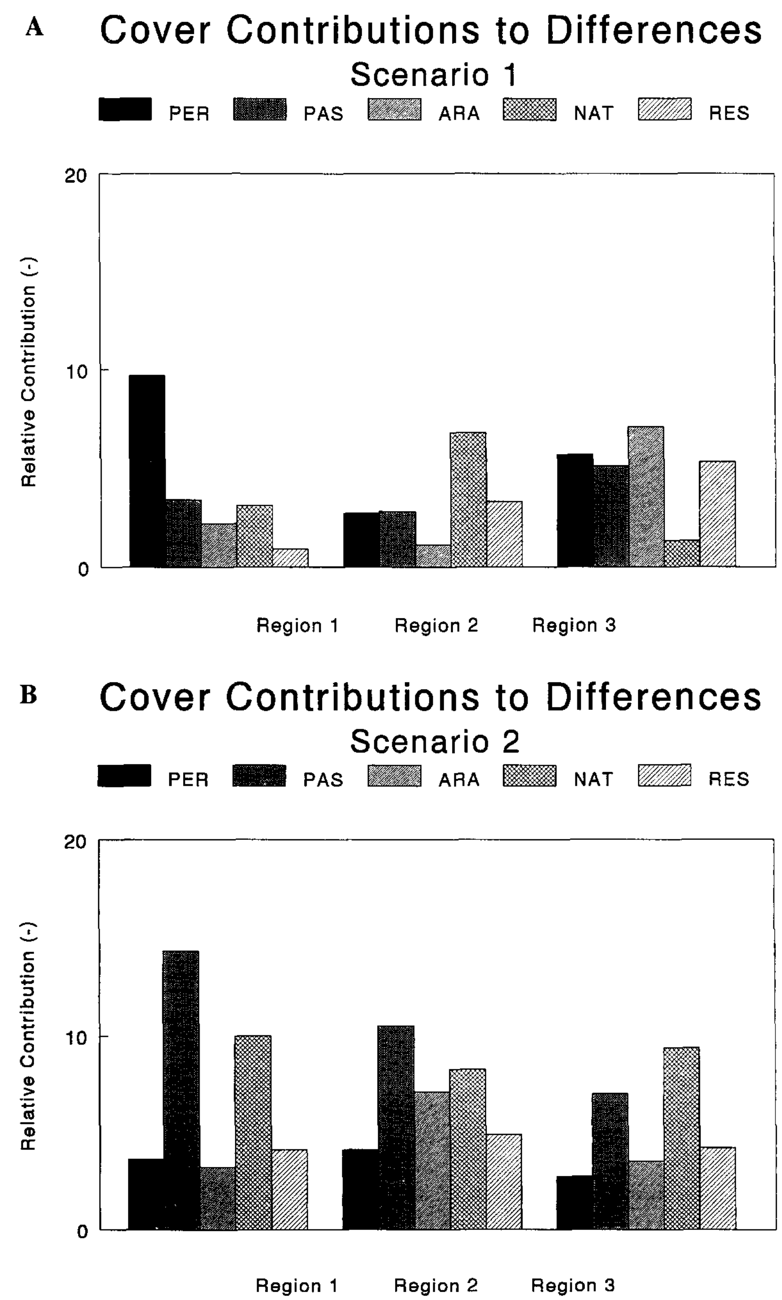

Fig. 8. The relative contributions of the different covers to the maximum difference in cover between simulations and the 1984 data.

can countries because international interactions are likely to take place. An advantage of such an upscaling exercise is that at higher aggregated scales global data bases are available describing most biophysical properties like altitudes, relief (NASA), vegetation (Olson et al., 1985), climate (Leemans and Cramer, 1991) and soils (FAO, 1993). Only when the CLUE-CR scaling up exercise is combined with a scaling down effort of the IMAGE 2.0 LCM model (Zuidema et al., 1994) may an operational and realistic Central American land use/cover change model evolve. The extension of CLUE-CR to other Central American countries can be done when similar data with similar resolution is available. Given the semi-quantitative CLUE approach, the rather common data applied and the non-region specific model procedures (like CRNEED, CHANGE, AUTODEV) in CLUE-CR the adaption and the tuning of a CLUE model to any other country or country-region should not pose too many methodological difficulties.

6. Conclusions

The described exercise of the construction, tuning, simulations and output evaluation of the initial CLUE-CR model allows us to conclude that the CLUE modelling framework is suitable to construct operational land use/cover change models. CLUE-CR is a geographically explicit model capable of simulating the effects of changing demographical and biophysical driving forces or their proxies on land use/cover change in Costa Rica, incorporating also feedbacks from land use/cover to those driving forces. By using different aggregation scales it can be demonstrated that local, regional and national trends can have opposite effects and results. The multi-scale aspect of the model allows the simulation of realistic system dynamics demonstrating the essential role of both top-down and bottom-up effects and processes. The multi-scale properties of the CLUE-CR model seem to stabilize model dynamics within realistic domains despite the limited data on which the model dynamics could be based.

There are no methodological constraints to scale CLUE-CR down and/or up and to link up with regional land use planning exercises and global climate change assessment studies. For the moment data limitations prevent such an exercise.

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