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Exploring Land Use Scenarios, An Alternative Approach Based on Actual Land Use

A. Veldkamp[a]* & L. O. Fresco[b]

[a]Department of Soil Science and Geology, P.O. Box 37, 6700 AA Wageningen, The Netherlands
[b]Wageningen Agricultural University, Department of Agronomy, P.O. Box 341, 6700 AH Wageningen, The Netherlands

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ABSTRACT

Land use scenarios should be able to describe land use as a result of changing biophysical and socioeconomic conditions, as well as the pathways of possible future developments including feedbacks between land use and its drivers. Several approaches exist, to date, to develop regional and national scenarios: (a) explorative biophysical studies which explore the biophysical boundaries of the 'solution space'; (b) socioeconomic explorative studies which couple calculated biophysical potentials with crude socioeconomic estimates. An alternative approach, based on actual and past land use and its biophysical and demographic drivers as integrated within the multi-scale land use change model CLUE, is presented and discussed. In combination with existing explorative approaches, this approach may contribute to more realistic land use projection scenarios. © 1997 Published by Elsevier Science Ltd

INTRODUCTION

A commonly applied methodology for exploring and planning land use are scenarios based on a combination of quantitative land evaluation methods with multi-criteria models such as interactive linear-programming models (de Wit *et al.*, 1988; WRR, 1992; Veeneklaas *et al.*, 1994). This methodology enables scenarios to be drawn up, in which biophysical and technical information on potential or improved land use is combined with various

*To whom correspondence should be addressed.

objectives derived from different policy views. Land use scenarios based on such exercises can be characterized as policy-oriented *explorative scenarios*. They are often used to indicate boundaries from a technical and biophysical point of view given socioeconomic, agricultural or ecological preferences. In order to explore land use potentials, each scenario calculates an optimum solution with respect to imposed biophysical and socioeconomic boundary conditions and constraints. Explorative studies can be subdivided into two different types: *explorative biophysical studies* which explore the biophysical boundaries of the 'solution space' and *socioeconomic explorative studies* which couple biophysical potentials with crude socioeconomic estimates of inputs and goals.

A considerable drawback of these explorative scenarios is the fact that they are *yield potential* driven which has proved to be a poor descriptor both of actual yields and of land use/cover distribution (de Koning *et al.*, 1993; Veldkamp & Fresco, 1995). An example is illustrated for Costa Rica in Fig. 1. where maize, rice and bean are distributions (1973 and 1984) and their water-limited production levels are compared. In explorative scenarios, calculated yield potentials are often directly translated into regional distributions under the assumption that the production will concentrate in those areas with the highest yield potentials. The Costa Rican example shows that there is only a weak relationship between crop yield potential and crop area distribution. In other words, yield potential cannot be used as a driving force for land use dynamics.

Another limitation is the way these calculated yield potentials are scaled down to attainable yields. This down-scaling is often done in a linear way or by a fixed percentage (Veeneklaas *et al.*, 1994; Zuidema *et al.*, 1994). This assumption implies that those factors and processes which determine yield potentials would also dominate the variability in attainable and actual yields, thus excluding all other relevant land use drivers. The same shortcoming applies also for future world food supply studies (Rosenzweig & Parry, 1994; Penning de Vries *et al.*, 1996). Moreover, the yield potential approach is currently not applicable to animal production.

Land covers cannot be based on crop yield potentials, because *land use* does not equal *crop yield*. Furthermore, potential yield levels play no direct role in land use decisions taken by land users. Any reduction in yield *potential* will not affect land use as long as this potential is far above an actual yield level, which is often the case. Even if potential yields are relatively low, land use practices such as irrigation and drainage can cause actual yields to be much higher than calculated water-limited yield potentials. On the other hand, some studies assume irrigation in areas where this is most unlikely (e.g. the Sahel and Amazon) (Penning de Vries *et al.*, 1996). Any description of the land use system without a dynamic human actor component will therefore never attain realistic value.

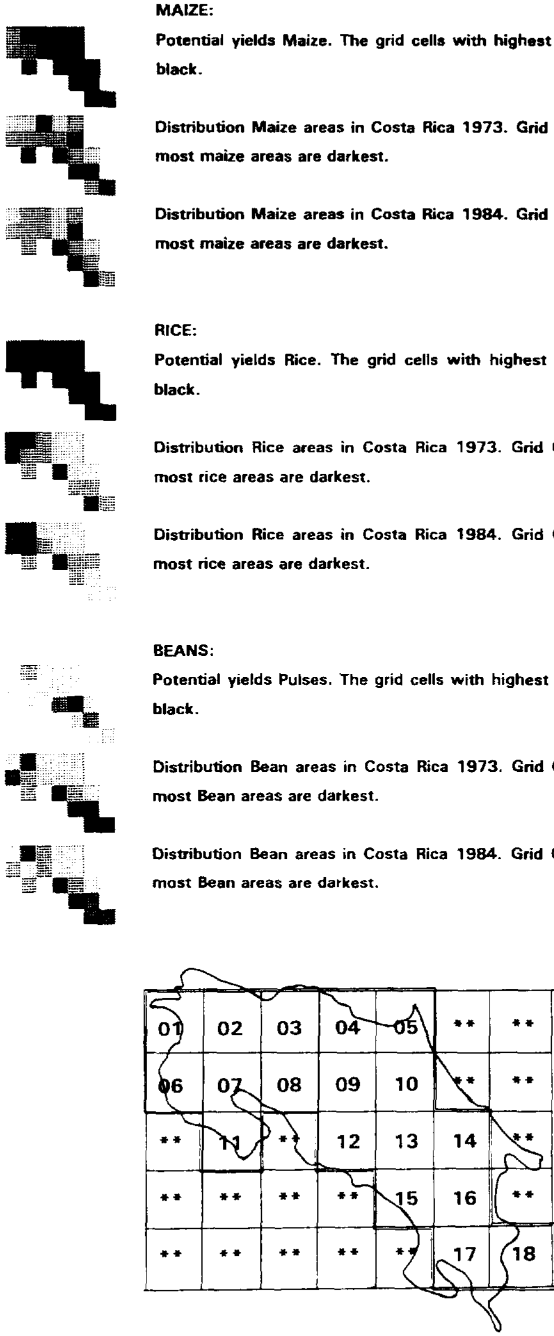


Fig. 1. Comparison of water-limited yield potentials and crop distributions in 1973 and 1984 for maize, rice and beans in Costa Rica. (Each grid covers 0·5°×0·5° latitude–longitude). Source: Veldkamp & Fresco (1995), p. 21.

Some other more detailed limitations of explorative scenarios for land use systems are listed by van Duivenbooden (1995) p. 141: (a) the limited number of production systems; (b) the absence of other economic sectors; (c) the neglect of urban systems; and (d) the absence of dynamic processes (e.g. changes in population, prices, biophysical conditions etc.). Another strongly neglected characteristic of the explorative scenarios is their lack of scale dynamics. Within land use/cover research the scale at which an analysis is conducted tends to affect the type of explanation given to phenomena (Fresco & Kroonenberg, 1992; Turner *et al.*, 1993). At broad scales, the high level of aggregation of data obscures the variability of situations and relationships. Broad-scale system descriptions are therefore considered to be inaccurate for regional and local assessments, because at the aggregate level key processes are usually masked. The development of fine-scale system models for every local situation would be both impractical and inadequate if there is no possibility of generalizing these models. Valid system models of meso-scale patterns of landscape changes should thus be based on the specification of regional scale processes, which themselves are more than the sum of local scale processes. There are actually two different scale effects: (a) each scale has its own specific processes and variables; (b) inter-relationships within a given set of variables change with scale. A comprehensive scientific explanation of the processes leading to land use changes can only be achieved by combining observations and explanations from different scale levels. The multi-dimensional character of the land use system complicates straightforward interpretations of its driving forces and their effects.

The final limitation of these explorative studies is that the applied crop growth simulation models cannot be scaled up to higher scales without taking into account the scale-dependence of processes and their effects (Holling, 1992). It is theoretically incorrect to scale up plot-based models to higher, more aggregated scales such as national or continental scales. The scale application domain of explorative scenarios is therefore very limited. As a result of the listed methodological shortcomings and the lack of feedback mechanisms the actual feasibility of biophysical explorative scenarios remains virtually unknown.

ALTERNATIVE SCENARIO STUDIES

Although there are other more interactive ways to make the land use scenarios such as offered as standard multiple decision tools in geographical information systems like IDRISI and ARCINFO, there is a growing need for more dynamic and scale-sensitive methods. Current explorative land use scenario types and multiple decision tools are therefore not very realistic.

The most logical way to improve these scenarios would be by a more complete integrated dynamic description of actual land use systems, including biophysical and human drivers and their scale hierarchies. A dynamic approach to model spatial and temporal land use/cover dynamics was undertaken with the CLUE (Conversion of Land Use and its Effects) framework (Veldkamp & Fresco, 1996). Based on this theoretical framework a first land use/cover pilot model (CLUE–CR) was made, which can simultaneously simulate local (approximately 56 km^2), regional (approximately 225–2025 km^2) and national (approximately 52,480 km^2) land use/cover changes in Costa Rica, including interactions between land use/cover and its drivers (Veldkamp & Fresco, 1995). The multi-scale aspect of the model allows the simulation of system dynamics related to the interaction of top-down and bottom-up effects and constraints (Fig. 2). CLUE can best be classified as a descriptive land use framework but its dynamic and multi-scale properties set it apart from the type of studies classified as descriptive by Rabbinge & van Ittersum (1994). For the moment CLUE–CR is used to demonstrate possible and plausible pathways of land use system development in response to certain events, impacts and policies at *local, national* and *regional* scales. To demonstrate some model characteristics a few scenarios of CLUE–CR are demonstrated.

CLUE scenarios

CLUE scenarios are made by changing, extrapolating and adjusting the relationships of land use/cover drivers and related land use systems. A theoretical example is given in Fig. 3, where two land use drivers α and β determine the development of a described hierarchical land use system (indicated by triangles) at a certain scale level. Temporal changes in α and β control the evolution of this system. A standard pathway scenario can be made by extrapolating the trends of both land use drivers for several years. Alternative scenarios are made by assuming changing relationships between land use and its drivers due to changing external conditions. Apart from changing the direct relationships between land use and its drivers, one can assume or introduce feedback mechanisms between certain drivers and land uses. An example is the introduction of an urbanization process related to the local (grid level) agricultural production. The response and development of the modelled land use system are relatively easily reconstructed. Usually these pathway scenarios can be expected to fall far below the possibility range (dashed box in Fig. 3), as generally indicated by an explorative scenario which is often based on optimal (maximum) conditions and possibilities.

Six scenarios for Costa Rica are presented and discussed (Fig. 4). The examples include three *policy oriented scenarios* of the land use/cover effects of: (1) urbanization; (2) abolition of national parks; and (3) extension of national parks. Three *system sensitivity scenarios* display system responses to: (4) prolonged soil erosion and soil fertility depletion; (5) crop disease in permanent crops below 300 m; and (6) a volcanic eruption. The scenario

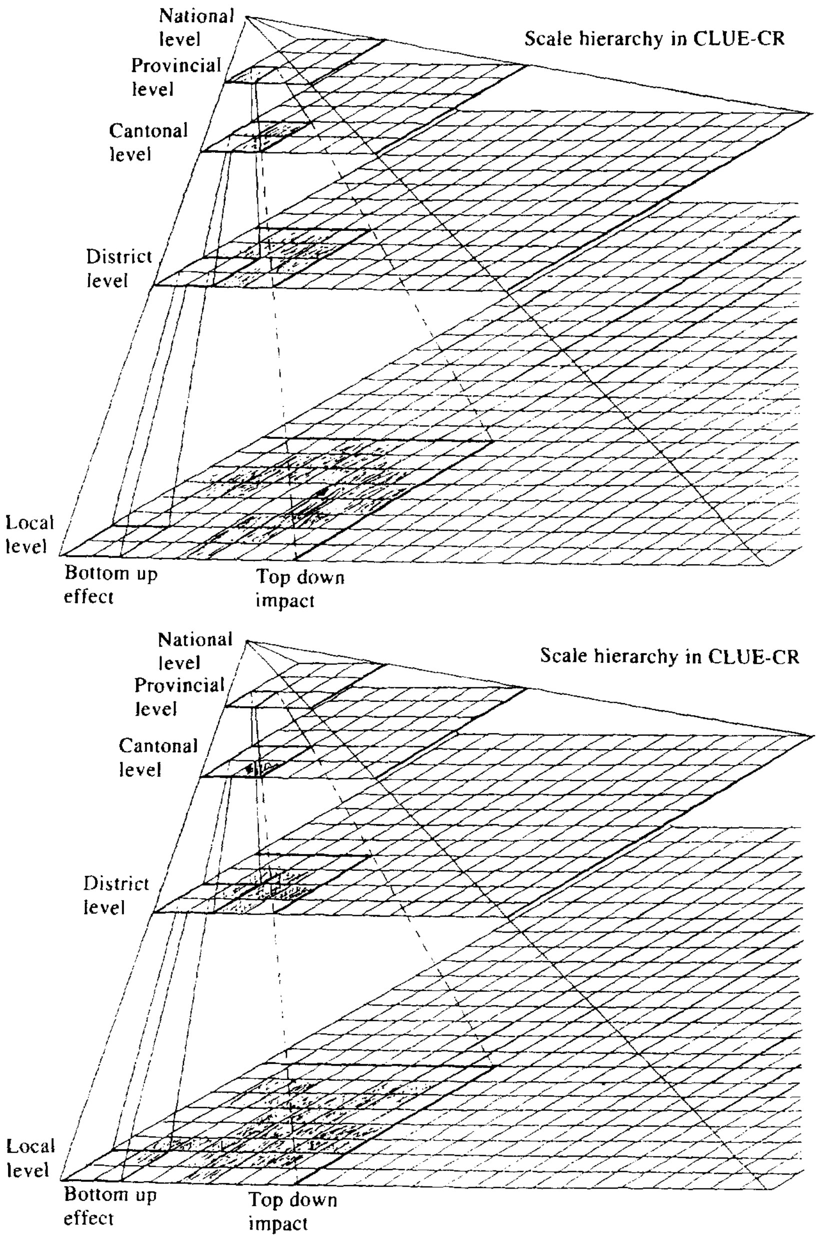


Fig. 2. The effects of different spatial scales in CLUE–CR.

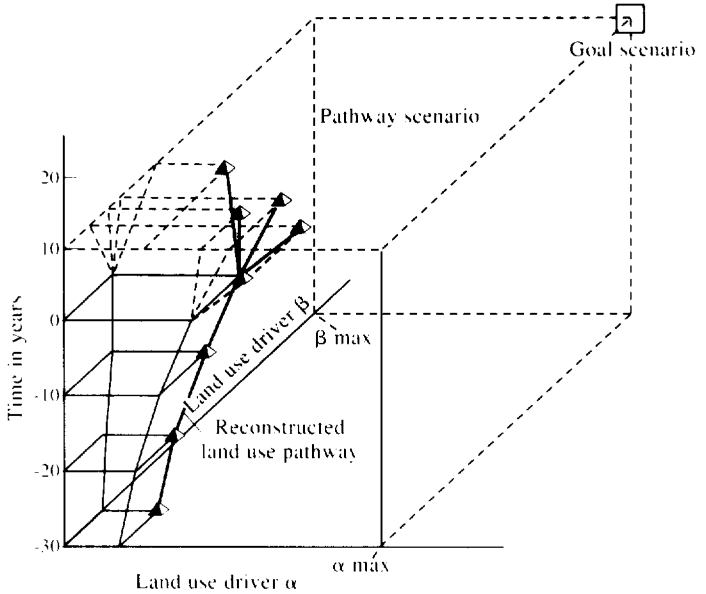


Fig. 3. The projection of a pathway scenario within the potentials of explorative scenarios.

outputs of these six simulations are all compared with a standard scenario (scenario 0) which is a linear extrapolation of the 1973–1984 land use/cover system to which the model was initially calibrated. The maps in Fig. 4 give the land use/cover outputs for the five use/cover classes (whose sum is 100%), after approximately two decades of simulated years. We will not discuss all scenario details and the changes which occurred during the simulated years but concentrate instead on the general principles and outputs of this type of scenario. To facilitate the display of temporal dynamics the results may be aggregated into three major biophysical regions and at national level (Fig. 5). As examples of the simulated land cover dynamics the standard scenario and scenario 3 are displayed for the three biophysical regions and the country as a whole (Fig. 6).

Policy scenarios

Scenario 1: urbanization

In this scenario the consequences of a policy stimulating urbanization are evaluated. As an urbanization driver the degree of regional self-sufficiency is used. Obviously, this scenario is sensitive to the threshold values for self-sufficiency and the selection of a major urban centre to which the rural population can migrate. This scenario demonstrates which regions perform

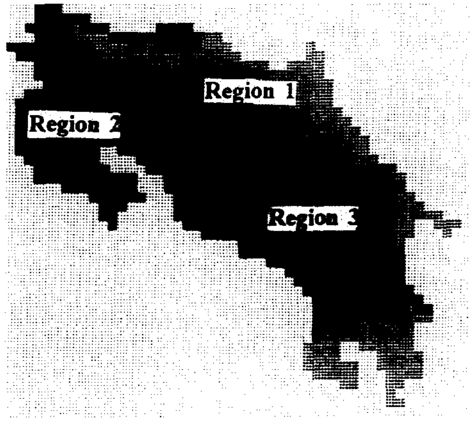
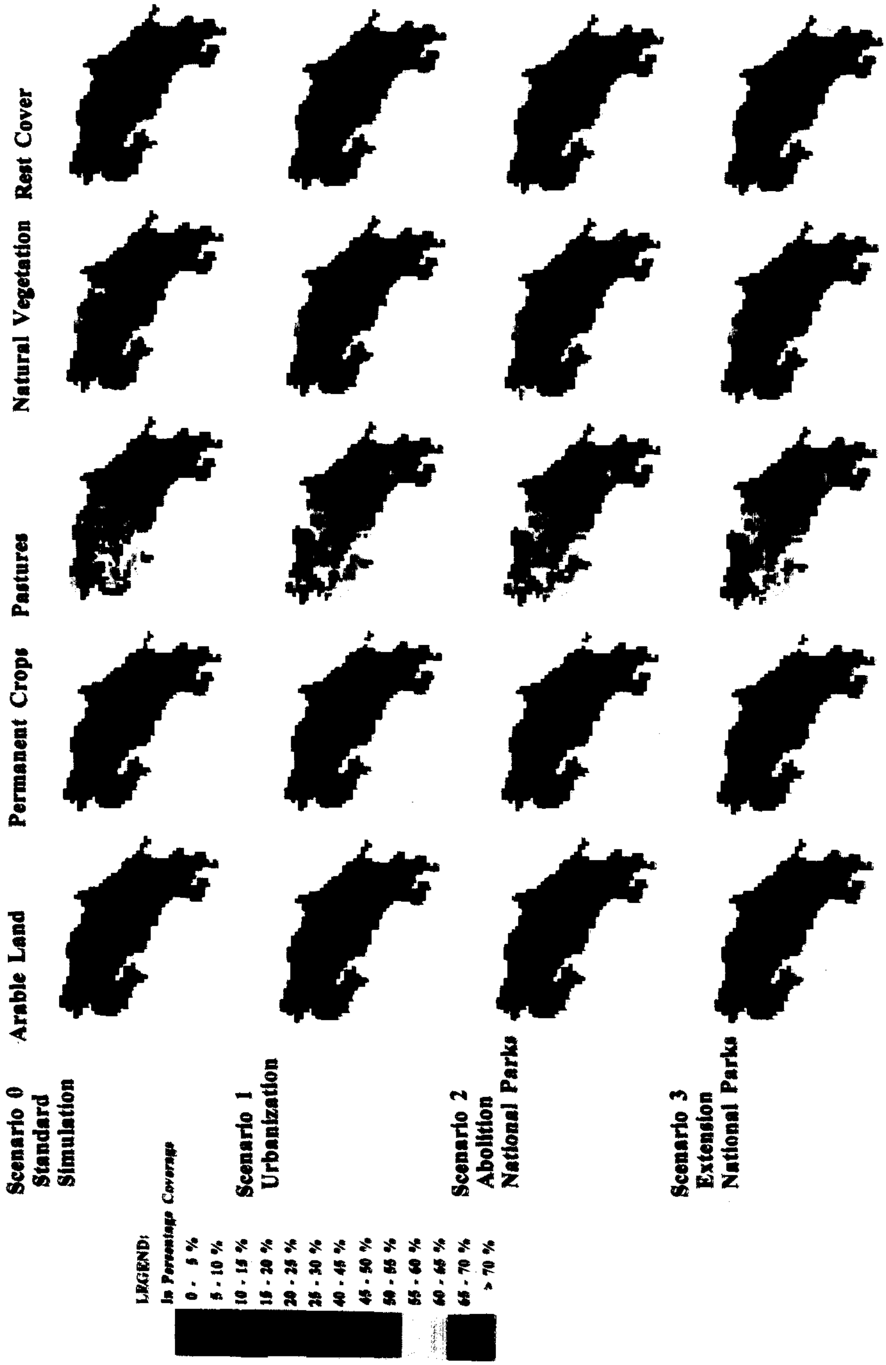


Fig. 5. The three biophysical regions used to aggregate the land use/cover changes.

near their carrying capacity under the calibrated conditions. An effect of this scenario compared with the standard scenario is that certain areas are abandoned in favour of natural vegetation, causing regrowth of natural vegetation. Furthermore, more pastures remain in production than in the standard scenario and permanent crop production is intensified in certain areas.

Scenario 2: abolition of national parks
This scenario simulates the effects of removing the protected status of all existing national parks. Furthermore, a certain migration into these parks is assumed. The migration rate was made a function of population density near the national parks and biophysical suitability of the park areas (Keogh, 1984; Veldkamp *et al.*, 1992). This scenario demonstrates clearly which national parks are most likely to be affected when their status is revoked. It confirms that the national park status is really necessary to protect most of the remaining natural vegetation in Costa Rica. However, it is noteworthy that not all national parks disappear under this scenario, suggesting that land pressure is not equally distributed throughout the country. This scenario is sensitive to the simulated migration rate.

Scenario 3: extension of national parks
In this scenario it is assumed that within 20 years the population in selected buffer-zones around national parks is gradually removed to urban centres, a kind of forced urbanization. It has, therefore, similar effects to the urbanization scenario. The areas with permanent crops and pastures are used even more intensively than in scenario 1, an effect which is probably due to the reduction of total available agricultural land in this scenario.


Arable Land
Permanent Crops
Pastures
Natural Vegetation
Rest Cover
Scenario 0
Standard
Simulation
Scenario 1
Urbanization
Scenario 2
Abolition
National Parks
Scenario 3
Extension
National Parks
LEGEND:
In Percentage Coverage
0 - 5 %
5 - 10 %
10 - 15 %
15 - 20 %
20 - 25 %
25 - 30 %
40 - 45 %
45 - 50 %
50 - 55 %
55 - 60 %
60 - 65 %
65 - 70 %
> 70 %

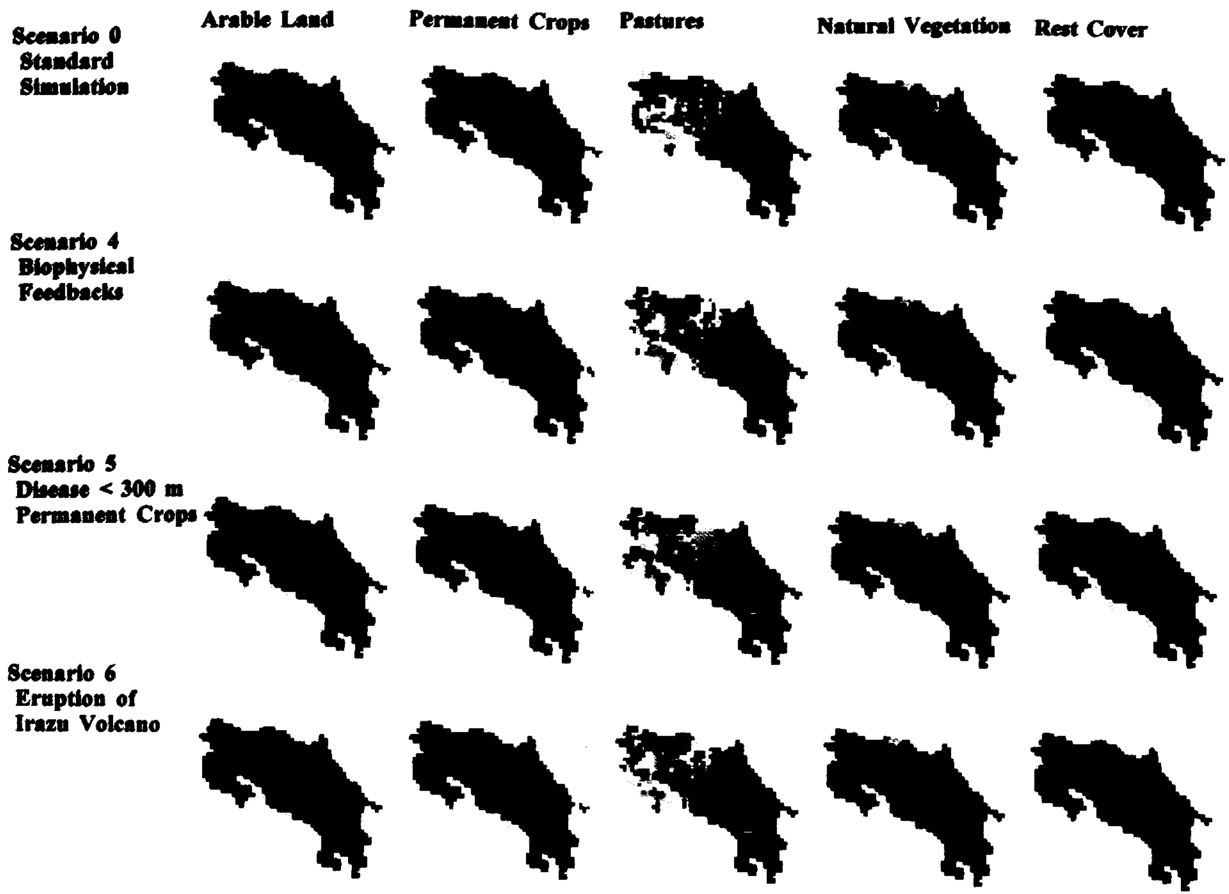


Fig. 4. Seven different examples of pathway scenario outputs after 21 simulated years with CLUE–CR. Maps display the five main land use/covers, permanent crops, arable lands, pastures, natural vegetation and rest. One grid is approximately 7·5×7·5 km (0·1°×0·1°).

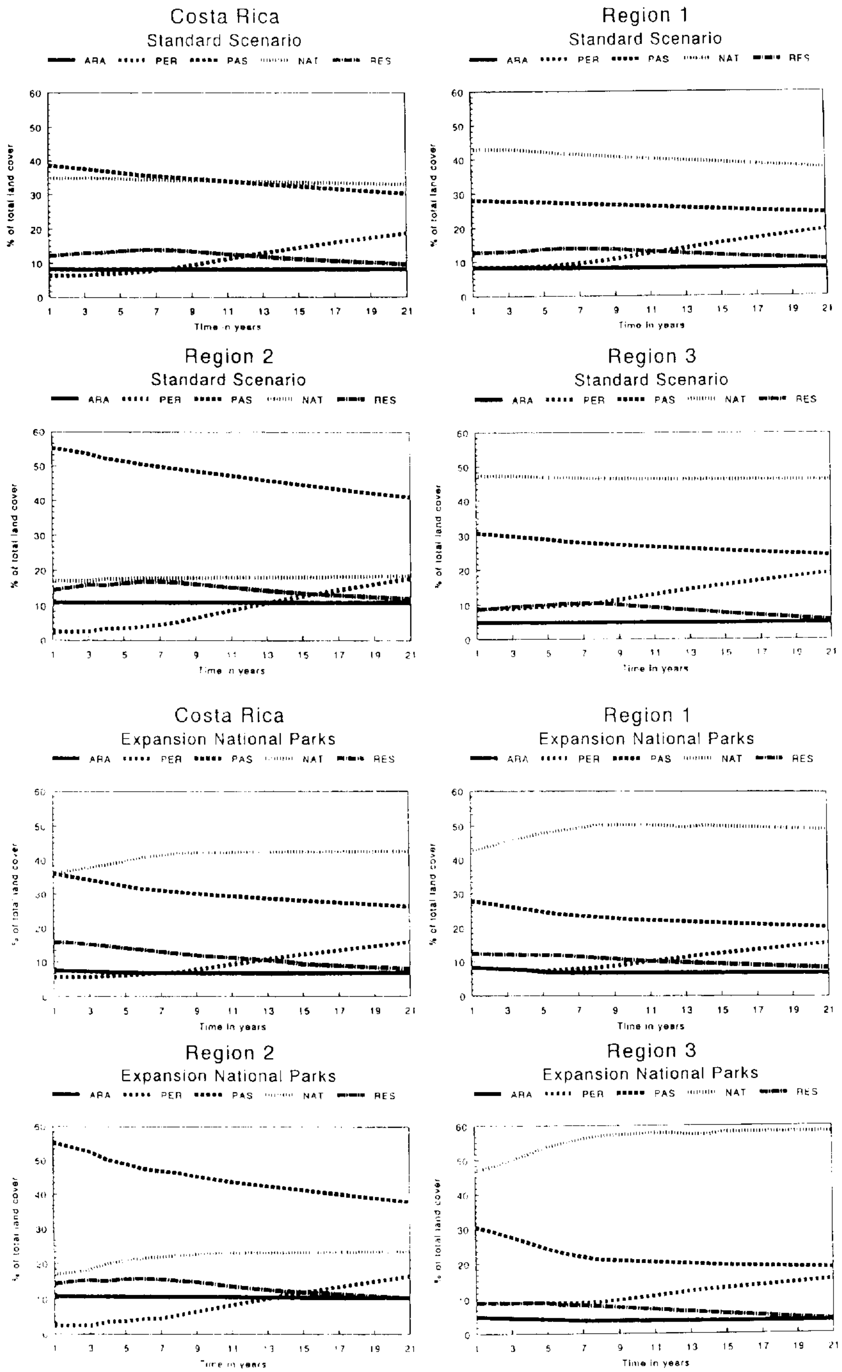


Fig. 6. The changes in land use/cover (standard scenario) during a 20 year simulation of CLUE–CR aggregated to regional and national scale. ARA, Arable land; PER, permanent crops; PAS, pastures; NAT, natural vegetation; RES, rest cover.

Sensitivity scenarios

Scenario 4: soil erosion and soil fertility depletion
Within this scenario the impacts of prolonged soil erosion and fertility depletion are simulated as yield reductions. Erosion is simulated to occur in relatively steep areas under perennial and annual crops (permanent crops and arable lands), whereas a reduction in soil fertility is assumed to occur in relatively remote areas with annual crops. This scenario includes an urbanization process to simulate a plausible demographic response to the simulated yield reductions. Compared with the standard scenario the biophysical suboptimal regions are clearly recognized by a relative decrease in arable lands and permanent crop areas. Several regions are almost completely abandoned in favour of natural vegetation.

Scenario 5: crop disease in permanent crops below 300 m
This scenario simulates the yield reducing effects of a permanent crop (like banana or cocoa) disease (during 15 yr) in the areas below the 300 m following a disease scenario as simulated by Chan & Jeger (1994). Again the urbanization response is included to allow a demographic response. There are clear similarities with scenarios 1 and 4, but in the affected areas considerably fewer permanent crops are grown due to the local/regional effects of the simulated crop disease.

Scenario 6: a volcanic eruption (Fig. 4)
In this scenario a plausible major eruption is simulated by the effects of ash fall in a plume-shaped region downwind of an existing active volcano (Irazu) (situated in grid no. 13 of Fig. 1) with an estimated recurrence interval of 1000 to 2000 years based on research at the Turrialba volcano (Reagan, 1987). In the central part of the affected region, still visible as a dark green area in the output, the ash cover is assumed to be too thick to allow agriculture for at least 15 years, whereas a boundary zone covered with less ash is affected by yield reductions for 15 years. An urbanization process allows the people of the affected area to leave for urban centres. Apart from the direct local/regional effects of this eruption, output differences with the standard scenario can be seen throughout the whole country.

DISCUSSION AND CONCLUSIONS

The six scenarios clearly illustrate the type of integrated scenarios which can be constructed, simulated and evaluated within the CLUE framework. One of the main assets is the multi-scale dynamics. Local and regional processes or events like urbanization (1), biophysical degradation (4), a crop disease (5) or a volcanic eruption (6) can display nationwide effects. Conversely, national processes or decisions such as policies concerning the status or extension of national parks (2, 3), have specific local and regional impacts.

Now that some results of CLUE scenarios have been demonstrated it is relevant to compare them with common explorative scenario methodologies. In Table 1 some general characteristics of both methodologies have been listed to facilitate this comparison. Explorative land use studies, although not time dependent, are essentially focussed on the technical, ecological, agricultural and economical possibilities and perspectives for the longer term, based on the limitations and potentials identified at the plot level. The applied models allow only a dynamic evaluation of crop production potentials; the technical, economic aspects are used as constraints within an optimization procedure but do not usually dynamically interact within the model. These models are very suitable for evaluating the possible effects of changing biophysical characteristics such as erosion and soil fertility on the production potential of selected crops. The translation of these potentials into real land use/cover changes remains the weak point.

Scenarios such as are made with CLUE are not focussed on crop yield potentials at all. They are based on a scale-dependent statistical description of past and actual land use distributions, taking both biophysical and demographical factors into account (Veldkamp & Fresco, 1995). This approach allows the incorporation of dynamic responses of the rural and urban population to biophysical changes. Yields are incorporated and used in the model but are not an outcome.

There have been attempts to incorporate a multi-period approach in explorative studies (e.g. Spharim *et al.*, 1992). This adaptation allows the incorporation of land use sequences or rotations and permits, to a certain extent, the incorporation of feedback effects. Another methodological problem of explorative scenarios is related to the application of multiple goal linear programming. Goal-oriented approaches are scale-specific (often single-scale) and thus automatically exclude multi-scale dynamics, which are an essential element of land use system dynamics (Turner *et al.*, 1993). The explorative scenarios are made scale-specific by aggregating data or simulation results to the desired scale level. This aggregation procedure is not without consequences, because it assumes that the crop/soil water processes at the plot level which form the basis for the biophysical assessments are not scale-dependent, an invalid assumption (Kolasa & Pickett, 1991; Holling, 1992).

Currently, the explorative scenarios are better linked to economic factors than the scenarios of CLUE, because the interactions and feedbacks between

TABLE 1
Comparison of characteristics of explorative and CLUE scenarios

Characteristic	*Explorative scenarios*	*CLUE scenarios*
Land use	$\sum$ (Crops)	$\sum$ (Land use/cover classes, sum = 100%)
Land use system	$\int$ (Biophysical factors, socioeconomic factors)	$\int$ (Past and actual land use, biophysical, demographic, and socioeconomic factors)
	$\int$ (Crop yield potentials)	
No. of scale levels	Single-scale system. Only bottom → up aggregation	Multi-scale system. Dynamic scale interactions (bottom → up and top → down)
Scale validity	Globally valid at plot scale	Site- and scale-specific, valid at different scales
Land use changes	Only as changes in calculated crop yield potentials	Simulated by their relevant drivers
Time horizon	None	A limited time horizon (< < 25 yr)
Socioeconomic factors	Act as constraints	No economic drivers/feedbacks included yet

the land use system and the economy are complex and scale-dependent and thus not easily incorporated (Dovers, 1995). Another limitation of CLUE is that the use of actual and past land use data puts considerable limits on the time horizon of its scenarios. It will probably always remain impossible to make reliable pathway reconnaissance surveys for longer time spans (> 20 yr) because too many degrees of freedom are involved. Because CLUE is based on past and actual land use system data it is difficult to incorporate new crops and technologies or land uses entirely because their scale-dependent relationships are unknown. However, for different reasons this is also the case with explorative studies.

The explorative scenarios are a well-established exploration tool to indicate the biophysical limitations and potentials of areas given certain socioeconomic conditions and constraints. As shown in Fig. 3, they produce a well defined multi-dimensional box projection mostly based on biophysical drivers within which the land use changes can take place. Pathway scenarios as applied in CLUE are unable to detect when system limits are reached. Especially for areas where actual land use is near its maximum potential it is essential to know these limitations. These should be described in such a way that their spatial and temporal variability and scale dependencies are clear. Such an integrated assessment can only be feasible when both explorative and CLUE methodologies are combined and integrated. The most logical combination is to apply explorative scenarios to define short- and long-term possibilities given certain biophysical, socioeconomic and political constraints as defined within a CLUE scenario. The outcome of these explorative scenarios may play a role in determining pathway developments of land use systems. Such a procedure would probably result in more realistic land use projections than with the various separate methodologies.

In particular, applications focussed on future world food supply and land use changes in a global change context could gain enormously from an integrated land use scenario approach. Along the pathway to, for instance a double atmospheric CO_2 concentration, the land use system will almost certainly have changed considerably by the ever-changing system conditions and drivers. These changes will lead to completely different land use systems than envisaged in current explorative scenarios, which usually combine current land use systems with projected biophysical constraints such as double CO_2. On the other hand, scenarios made with CLUE cannot assess the potential effects of double CO_2. Future efforts in land use studies should therefore be based on an integration of both the explorative and the pathway (CLUE type) approaches in order to produce more realistic and dynamic land use projections and sensitivity assessments.

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