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CLUE: a conceptual model to study the Conversion of Land Use and its Effects

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Abstract

A dynamic model to simulate Conversion of Land Use and its Effects (CLUE) is presented. For an imaginary region, CLUE simulates land use conversion and change in space and time as a result of interacting biophysical and human drivers. Within CLUE regional land use changes only if biophysical and human demands cannot be met by existing land use. After a regional assessment of land use needs, the final land use decisions are made on a local grid level. Important biophysical drivers are local biophysical suitability and their fluctuations, land use history, spatial distribution of infrastructure and land use, and the occurrence of pests and diseases. Important human land use drivers in CLUE are population size and density, regional and international technology level, level of affluence, target markets for products, economical conditions, attitudes and values, and the applied land use strategy. Initial CLUE simulations suggest that the integrated land use approach of CLUE can make a more realistic contribution to predictions of future land cover than currently used biophysical equilibrium approaches.

Keywords: Land cover change; Land use planning

1. Introduction

One of the most pressing issues of global change research are the interactions of land cover changes with global climate. By far the most important factor in land cover modification and conversion is human use, rather than natural change (Turner et al., 1993). Changes in land cover cannot be understood therefore, without a better knowledge of the land use changes that drive them, and their links to human causes (Ojima et al., 1991). While much land use takes place at the scale of small individual units of production, its impact is global and cumulative.

Land use can be looked upon as a multi-dimensional ($\geq$ 4D) process which consequently poses many difficulties for proper description and classification. Land use can be defined as the human activities that are directly related to land, making use of its resources or having an impact on it through interference in ecological processes that determine the functioning of land cover (Mücher et al., 1993). An extensive description of land use includes the sequence of operations, their timing, the applied inputs, the implements

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and traction sources used, and the type of output (Stomph et al., 1994). In the context of global change, the formal characteristics of land use, i.e. its effect on cover structure, phenology and composition, is more relevant than the purpose or function of land use.

Human interference in land cover is greatly dependent on land-related biophysical constraints and human perceptions of these. In this paper these land constraints will be referred to as the biophysical drivers of land use. Land use is thus determined by the interaction in space and time of *biophysical* factors (constraints) such as soils, climate, topography etc. and *human* factors like population, technology, economic conditions etc.

The observation that the effects of land use drivers are usually region-specific does not rule out the existence of a general framework for modelling land use conversion and changes as is proposed here. First, we describe the general principles of how biophysical and human factors can drive land use, followed by a description of CLUE which acts as an operational dynamic framework which establishes formal linkages between biophysical and human drivers of land use. Within CLUE examples are given of assumptions based on the general land use driving principles. These assumptions pcımit the construction of a first CLUE prototype which describes the interaction of biophysical and human land use drivers on a regional level with tentative linkages to smaller and larger scale levels. Model operations and assumptions will be discussed followed by a purely theoretical simulation run demonstrating the effects of various land use drivers in an imaginary region.

2. General principles of land use drivers

Potential biophysical factors are well known from land evaluation and agronomic research (FAO, 1976,1993). In contrast, human factors in respect to land use are less well systematic described and investigated (Gallopín, 1991) although recently Turner et al. (1993, pp. 22–23) have drawn up a complete list. Based on such previous work, the following list of land use drivers is proposed as potential drivers to be applied in CLUE for any selected region. Each driver can be translated into a set of decision rules and included in the CLUE model.

2.1. Biophysical drivers

1. Initial biophysical suitability of the land for crops and land use types is related to climate, relief, soil etc. This overall suitability is the outcome of a land evaluation using generally accepted assessment methods based on assumptions of suitabilities according to FAO crop requirements (FAO, 1976,1993).
2. Some biophysical characteristics, like precipitation, temperature etc., display strong annual or seasonal fluctuations causing yield fluctuations in time. These fluctuations can have different impact on the different land use systems and are felt by land users as risks (Huijsman, 1986; Anderson and Hazell, 1989; Fresco and Kroonenberg, 1992).
3. Effects of past land use. Biophysical degradation of land may be caused by prolonged use or mismanagement. Biophysical degradation is often related to erosion, poor soil fertility status, soil compaction etc. (Juo and Lal, 1977; Dalal and Mayer, 1986). Upgrading of the biophysical land suitabilities may result from certain permanent land improvements like drain pipes, terracing, irrigation scheme etc. These cumulative effects of past land use can serve as a feed back mechanism to assess the sustainability of land use systems.
4. Pests, weeds and diseases reduce yield levels. Their impact can have local as well as regional effects for one or all crops grown in the region under study (Diekman, 1978).

2.2. Human drivers

Of the human drivers, the role of population growth is still a subject of much discussion. Some general relations have been statistically analyzed and investigated (Lee, 1986; Meyer and Turner, 1992; Bilsborrow and Okoth-Ogendo, 1992). The role of economic and institutional factors is certainly more dominant than is now assumed in

CLUE, but is minimized for practical reasons in the model.

Population

1.1. Population size and density determine the demands for food and monetary income. Food can be taken as a proxy for primary agricultural products (food, animal products, basic fibres and export crops).

1.2. Urban expansion rate is proportionally related to population growth.

1.3. Labour force availability is a function of population size and density.

Technology level

2.1. Technology level is a key determinant in the land use operation sequence, and thus in attainable yield levels (Lee, 1986).

2.2. Local land use types reflect regional technology levels, while commercial land use types producing for the (inter)national markets reflect the usually higher (inter)national technology level. As a result, yields are closer to potential levels for cash crops. Certain types of technology such as irrigation and fertilisation can potentially overrule natural biophysical limitations (Brouwer and Chadwick, 1991).

Level of affluence

3. The level of affluence determines the regional food basket and thus the composition of the food demand. Therefore, the level of affluence immediately affects the regional land use strategy. At low levels of affluence a food security strategy is applied first, while high levels of affluence often result in financial security strategies.

Political structures

4. Political structures may strongly determine the applied land use strategy. This can be done directly, by dictating by direct rule (Central ruled economies) or indirectly by financial stimulation policies of certain land use options (European Union). As the exact mechanisms of such political tools are too complicated to allow a flexible application in CLUE, only stable political conditions are applied within CLUE.

Economic conditions

5.1. Market mechanisms and trade may influence land use within any specific region. Often trade barriers and other artificial rules frustrate the natural market mechanisms and lead to 'unexpected' agronomic effects. As the economic basis of CLUE is still too weak, trade barriers and other more complicated economic mechanisms are not included in the model at this stage.

5.2. Each commercial land use system must meet certain minimal economical conditions to be able sell its products. Examples are minimum production volumes, minimum quality, an infrastructure to facilitate transport etc. These minimum requirements make some areas within the simulated region more suitable for commercial land uses than others.

5.3. (Inter)national trade income and yield surpluses over subsistence level determine the sensitivity of a land use system to trade and crop yield fluctuations, and are reflected in the land use strategies.

Attitudes and values

6. Regional attitudes and values can lead to specific social requirements and objectives. These may result in very specific land uses, such as the need for cattle to gain social status.

3. Model description of CLUE

CLUE serves as a tool through which the various biophysical and human land use drivers can be combined and interact in determining land use within a region. In order to demonstrate the potential of CLUE applications, various example assumptions about most discussed drivers are made and incorporated within the prototype. Both the simulated example region and the simulated time span are currently dimension-neutral. Further calibration and application will require also careful tuning of both spatial and temporal scales.

3.1. Model type

CLUE is a discrete finite state model (Ziegler, 1976) written in PASCAL and run on a VAX-4300 (it takes about 2.30 min CPU time for a run of approximate 500 time steps), integrating environmental modelling and a geographical information system. CLUE can be classified as a cross-disciplinary model linking several disciplines by relationships and feedback loops (Steyaert, 1993).

Due to the qualitative approach, the adaption and tuning procedure of CLUE to any specific region should not pose too many difficulties, but still requires a large amount of data on various subjects within the selected region.

4. Model structure and inputs

4.1. Overall assumptions in CLUE

a. Agriculture is the main employment and income generator in the simulated region. Food is produced within the simulated region or traded for cash crops which was produced in the region.

b. Land cover categories are agricultural systems, natural vegetation cover and towns.

c. Land use changes are only established when biophysical and human demands can not be met any more by the existing land uses.

d. A grid-cell is the smallest unit of analysis and is assumed to be internally uniform.

e. By incorporating yield and money surpluses as reserves for two years, seasonal and annual yield fluctuations have no direct effect on the land use conversion and changes.

f. Land use modifications like higher inputs related to increasing management and technology levels are not considered as a change in land use. It has to be noted however that changing input levels will almost certainly affect the land cover characteristics.

4.2. Simulated land use types in CLUE

Within the CLUE prototype ten different land use types (Table 1) typical for the lower latitudes are available. For each land use type the cover characteristics (%) without biophysical limitations are available on a monthly basis (Table 2). The land use covers change over the growing seasons. In reality the land cover is also determined by the land suitability and the occurrence of pests and diseases. The available land use (LU) systems can be provisionally divided into four partly overlapping groups, food-producing-land-use (LU1, LU2, LU3 and LU4), socially-related-land-use (LU4, LU8 and LU10) commercial-land-use (LU5, LU6 and LU7) and 'natural'-land-use (LU8 and LU9).

4.3. Characteristics of the region in CLUE

The imaginary region is represented as a gridded scale neutral matrix ($23*23$) with the following grid-specific characteristics:

a. Suitabilities for all ten possible LU types. Within CLUE the suitability is rated from not suitable to extremely suitable. The suitability

Table 1
Minimum economic age and rotation length of the 10 different land use types

LU no.	Min. econ. age (yrs)	Rotation length (yrs)	Crop systems of land use type
LU1	2	2	Rotation of maize, beans and fallow
LU2	1	1	Rotation of groundnut and sorghum
LU3	3	1.5	Cassava
LU4	5	2	Range land
LU5	1.5	1.75	Pineapple plantation
LU6	3	1	Banana plantation
LU7	6	1	Tea plantation
LU8	0	1	Forest/natural vegetation
LU9	–	–	Waste land, no agriculture/vegetation
LU10	–	–	Town

Table 2
Vegetation cover during growing season on monthly basis without biophysical limitations

LU type	Month no:																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
LU1	10	30	80	100	100	0	0	5	10	30	50	80	0	10	20	40	45	50	60	65	67	70	71	73
LU2	10	40	50	80	0	0	5	15	30	50	90	90	10	40	50	80	0	0	5	15	30	50	90	90
LU3	10	30	50	80	75	70	75	80	90	90	90	95	95	95	95	95	95	95	0	5	10	20	25	30
LU4	100	100	100	100	100	95	95	95	100	100	100	95	100	100	100	100	100	95	95	95	100	100	100	95
LU5	10	30	60	65	65	65	65	70	80	85	85	85	90	90	90	90	90	90	90	90	0	5	10	15
LU6	40	60	80	100	100	100	100	100	100	100	100	100	40	60	80	100	100	100	100	100	100	100	100	100
LU7	100	100	100	95	100	100	100	95	100	100	100	95	100	100	100	95	100	100	100	95	100	100	100	95
LU8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
LU9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LU10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

maps (Fig. 1) indicate various initial suitabilities for each land use type. To create sufficiently diverse conditions, the selected suitabilities only partly overlap each other (Fig. 1). The region is designed to incorporate the transition from a semi-arid to humid tropical climate with an intermediate subregion of highlands. Locally, patches (grids) of unsuitable land (e.g. mountain tops or lakes) are found. The suitabilities for the commercial crops are only indicated by non-suitable or extremely suitable, because land (grid) is considered suitable when the LU related inputs (technology level) can compensate all land related biophysical limitations. The land use suitabilities can change during a simulation by feedback mechanisms of land use practises and suitability effects.

b. Infrastructure status. A given infrastructure (road network) is assumed to exist within the region (Fig. 2).

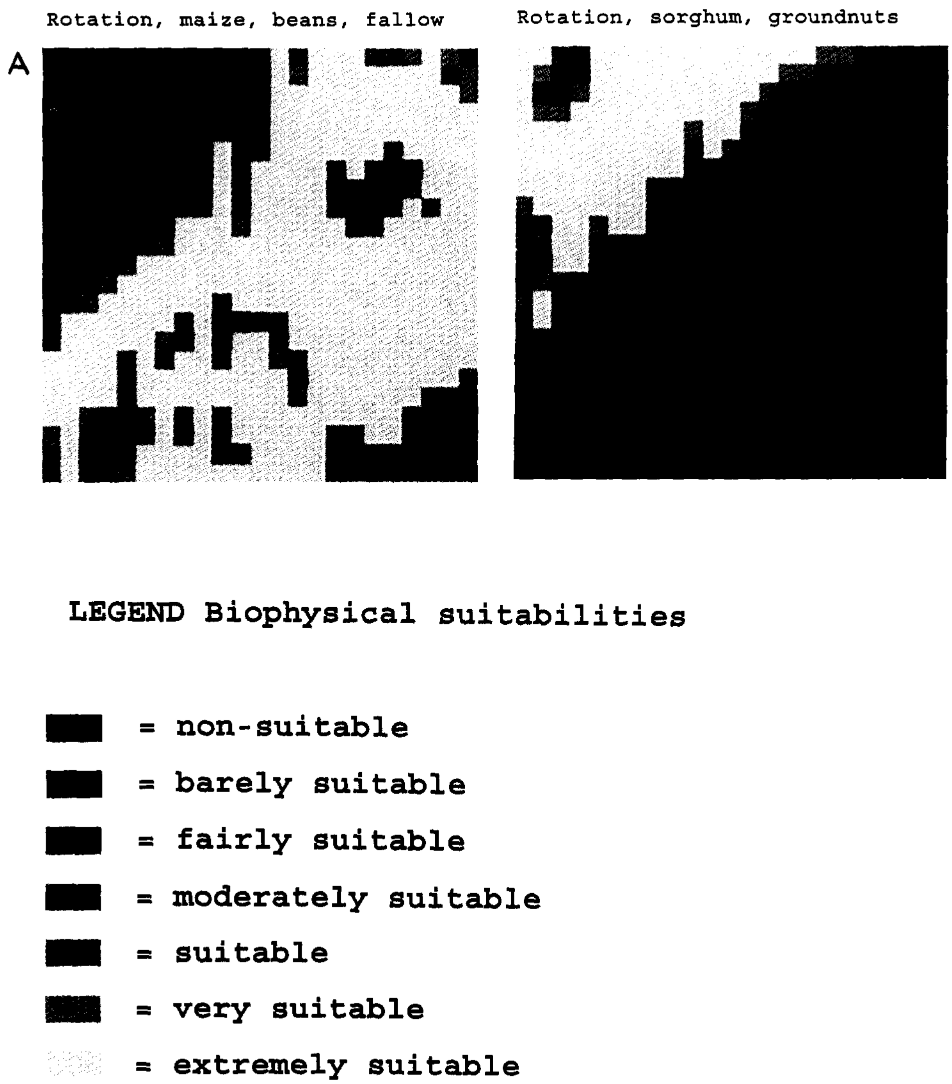


Fig. 1. Suitability maps of the simulated region for the 10 land use types.

c. Initial distribution of land use types is shown in Fig. 2. All ten land use types are present within the region to give them all an equal start. At the start of the model simulation the commercial land uses are situated along the existing infrastructure. All initial land use types are old enough to allow changes (e.g. no young perennial plantations).

5. Schematic overview of modelling sequence in CLUE

The sequence of land use conversion and changes within a CLUE simulation is based on the following modules (Fig. 3):

1. a *regional biophysical update module*, simulating effects of biophysical processes and factors

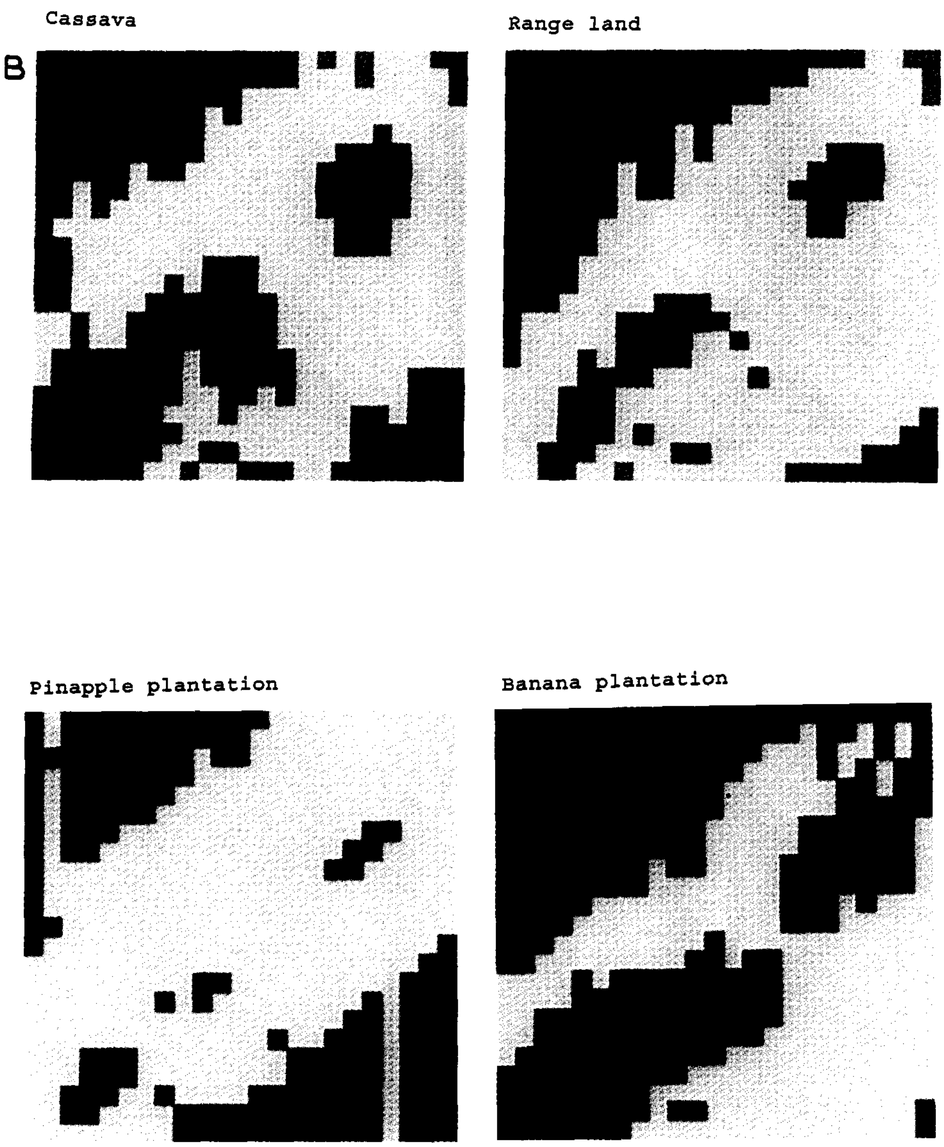


Fig. 1 (continued).

like diseases, land use history etc. for the entire region;

2. a *regional land use objectives module*, which formulates land use wishes and requirements based on biophysical and human factors/conditions, considered at a regional level;

3. a *local land use allocation module*, which attempts to change the land use at the grid level within the region according to certain land use allocation schemes (Fig. 4).

The model works on time steps of one month allowing output of the regional coverages for each month. The changes in land use types however, are made based on decisions for each year, the selected update interval. The actions of the biophysical module, land use objective module

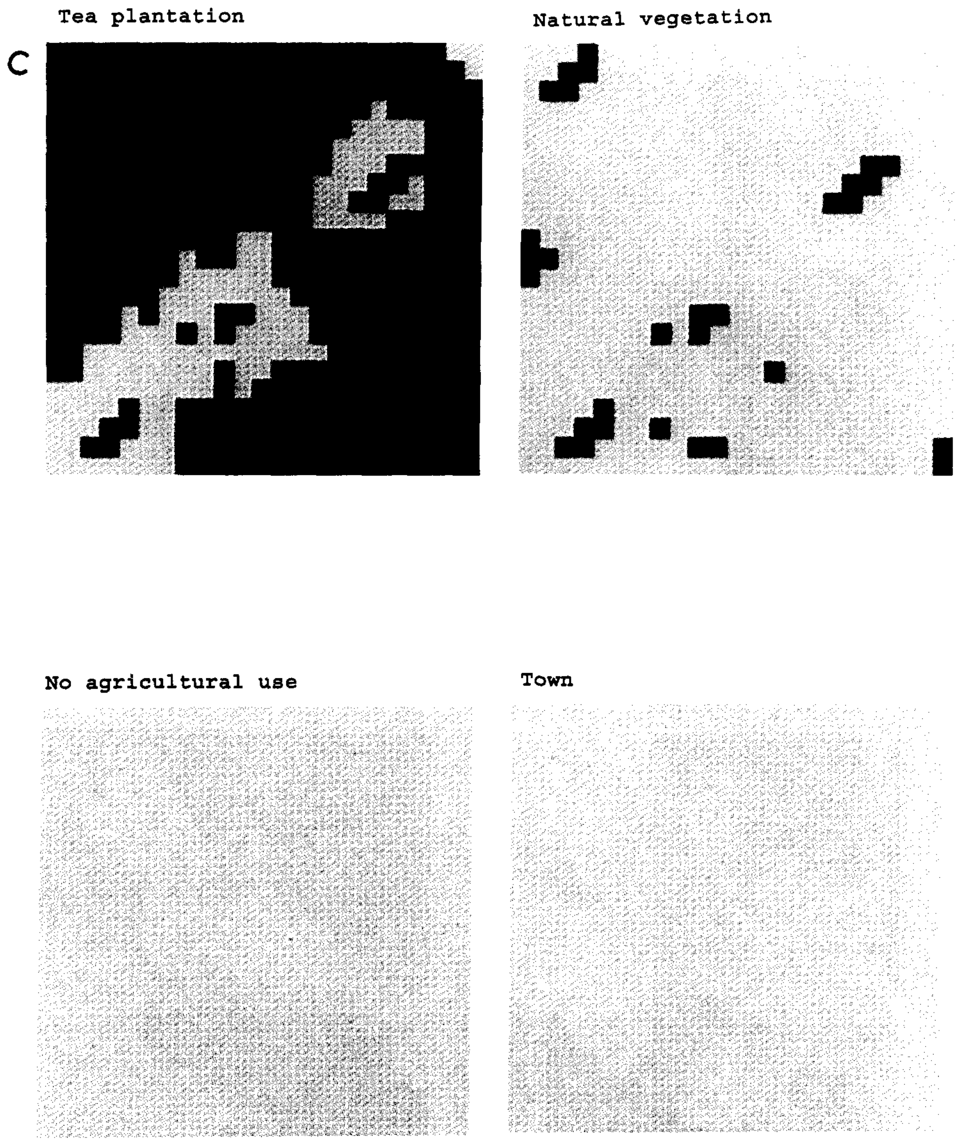


Fig. 1 (continued).

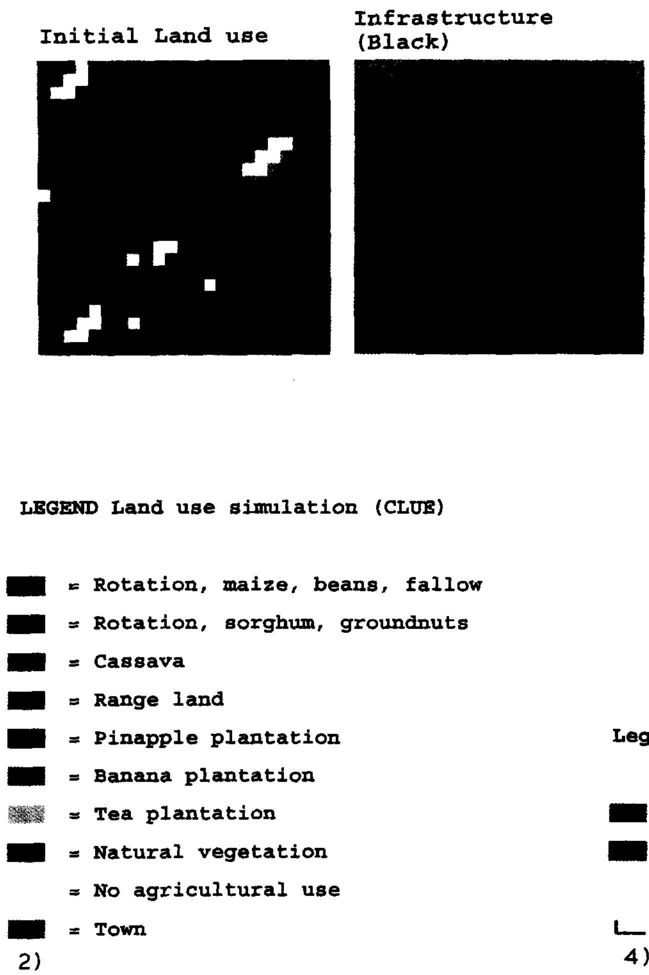
and the land use allocation module which take place each year during the simulation are described in a qualitative way below.

6. Regional biophysical update module

a. *LAND-SUITABILITY = f(land use history)*

Suitability update for land use history. After each year an update of the land use ages is made to allow the incorporation of feed back loops for prolonged land use. Three examples of over-use effects are currently incorporated in CLUE:

- After more than 20 continuous years of cassava (LU3) the suitabilities for LU1 LU2 are severely reduced due to low nutrient status (Cock, 1985).
- After more than 15 continuous years of grazing the suitabilities of LU1, LU2 and LU3 are somewhat reduced due to compaction (Bouma, 1989).
- After more than 20 continuous years of tea all



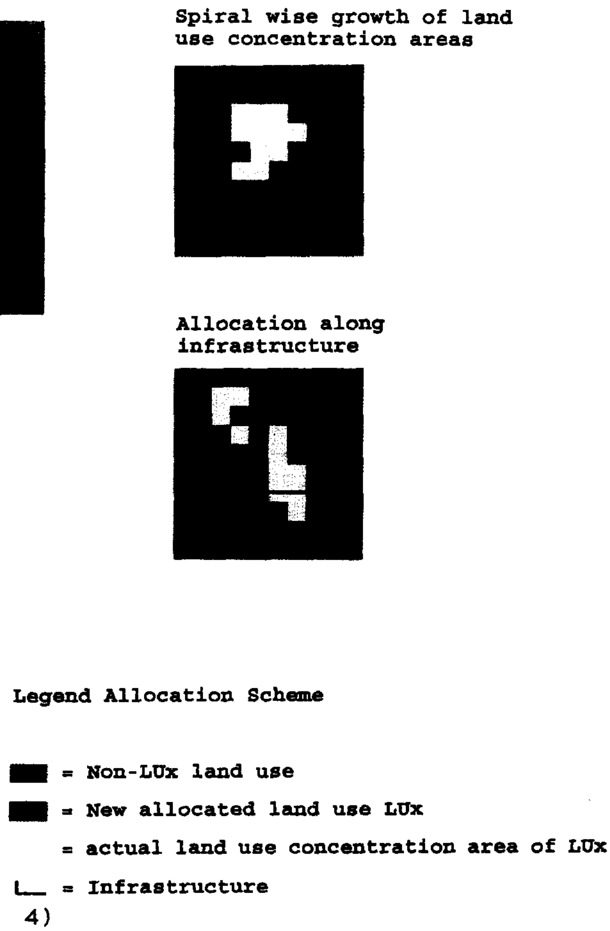


Fig. 2. Initial land use and infrastructure in the simulated imaginary region.

Fig. 4. The principles of the two land use allocation procedures.

other suitabilities are severely reduced due to extremely low soil pH (Webster and Wilson, 1980).

b. In case of a pest or disease outbreak for a certain crop, its geographic migration is simulated. It is currently assumed in CLUE that diseases spread along the existing infrastructure, combined with a grid to grid contamination. After a while the disease can spread over the entire region (migration speed of a disease is a model input), but does not always reach all grid units (depends on land use pattern) (Diekman, 1978). The effect of a disease is simulated by a temporary grid unsuitability for the diseased crop. After a remedy is found for the disease or a resistant stock becomes available (input) the original suitabilities are restored (Zadoks, 1971). The outbreak and persistence time of pests and diseases are model inputs.

c. *GRID-YIELD-LEVEL = f(annual fluctuations + suitabilities + effects of pests and diseases)*

Annual fluctuations in yield levels are due to climatic dynamics or pests. It is assumed that yield levels can fluctuate up to 80% of the mean yields as a result of short-term biophysical dynamics (e.g. drought). In CLUE these changes are evaluated annually and simulated by assumed recurrence frequencies (model input), causing fluctuations in regional yield levels. Apart from yield reduction by biophysical processes, pests may reduce yields for the entire region (e.g. plague of locusts) (Anderson and Mistretta, 1982).

d. *REGIONAL AVAILABLE FOOD / MONEY = f(land use types and their coverage resp + grid yields + economic value + technology level + food / money reserves)*

The existing land use types and their yields are determined for the entire region. Combined with the existing technology level, economic values and the two years of food/money reserves, the food/money availability in the region can be calculated.

7. Land use objectives module

Following these regional biophysical assessments the land use objectives and decisions of

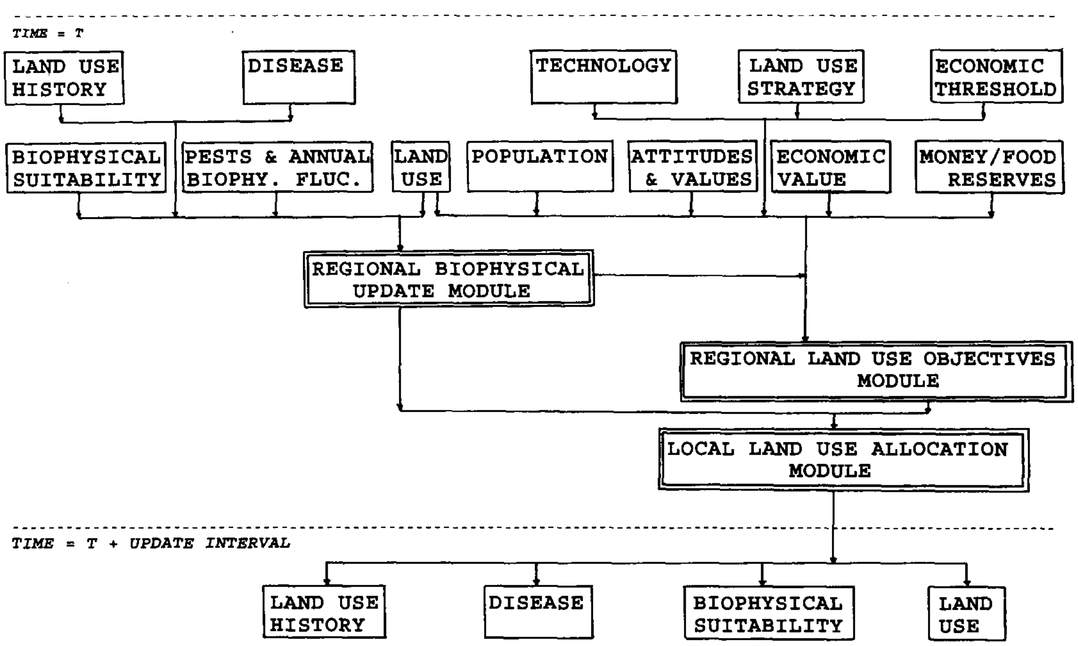


Fig. 3. Overview flow chart of the three modules within the CLUE model.

land uses are simulated. These decisions concerning the need and importance of each land use are made for the entire region for each year (update interval). However, the final decision whether to change existing land use is made in the land use allocation module at the local grid level. The following factors are selected in the CLUE prototype to determine the decisions concerning preferred land use changes on a *regional* scale:

a. *FOOD / MONEY-DEMAND = f(population size)*
MANAGEMENT-LEVEL = f(population size)
URBAN EXPANSION = f(population size)
Population (number of mouth to feed, labour force and urban inhabitants). A fixed population growth rate is assumed as long as a food self sufficiency condition exists. As more labour becomes available a higher management level is reached contributing to an increase of yield levels. However, population growth is assumed to lead to urban expansion causing a reduction of the available land for agricultural purposes.

b. *YIELD-LEVEL = f(technology level)*
LAND-USE-STRATEGY = f(regional technology level)
Technology level on regional and (inter)national scale. It is assumed that technology level increases gradually over time and causes a yield increase in time. There are two relevant technology levels, the regional technology level affecting food crops (LU1, 2, 3, 4) and an (inter)national technology level which directly affects yield levels of commercial LU for the (inter)national market (LU5, 6 and 7). The applied land use strategies are assumed to be related to the regional technology level. As the regional technology level increases the related land use strategies change from food security to a more commercial strategy.

c. *LAND-USE-VALUE = f(land-use-strategy)*
Values and boundary conditions of land use. The value of land use products change over time with regional attitudes and values, technology level and the economic situation. As these factors are not easily predictable, the land use type values are provisionally linked with the land use strategies.

A commercial LU type aimed for the (inter)national market requires a minimum critical product volume (size), quality and infrastructure to make it economically feasible. These minimum requirements act as threshold values.

d. Human 'survival' strategies. It is assumed that the people in the simulated region base their decisions concerning land use on strategies which change over time with social, technological and economical developments. The CLUE prototype has four different land use strategies which are all related to the regional technology level (Table 3). When regional technology level and the level of affluence increase, the land users adapt gradually (within decades) to more (inter)nationally oriented land use strategies. CLUE is currently

Table 3
Relative values and preferences of the different land use strategies

LU no.	Rel. values LU per strategy				Rel. preference for LU per strategy			
	strat.1	strat.2	strat.3	strat.4	strat.1	strat.2	strat.3	strat.4
LU1	4	3	2	1	7	1	1	0
LU2	3	2	1	1	2	0	0	0
LU3	4	3	2	2	1	1	1	1
LU4	4	3	3	2	0	1	1	0
LU5	2	3	4	5	0	1	2	3
LU6	2	3	4	5	0	1	2	3
LU7	2	3	3	4	0	1	1	2
LU8	1	2	2	3	0	0	0	0
LU9	0	0	0	1	0	0	0	0
LU10	0	0	2	2	0	0	0	0

initialized by a food-security strategy, followed by a second strategy which is still aimed at food security but with a change in the regional food basket (more LU3 at the cost of LU2). The third strategy involves a gradual introduction of cash crops (commercial land use) followed by a strategy completely aimed at producing cash crops and thus at commercial land use.

e. *LAND-USE-DEMAND = f(attitudes and values)*

Attitudes and values. Regional demographical and ethnological factors can strongly determine land use preferences. Examples are decisions related to social status and social 'needs'.

Two examples of the latter needs are incorporated within the prototype CLUE.

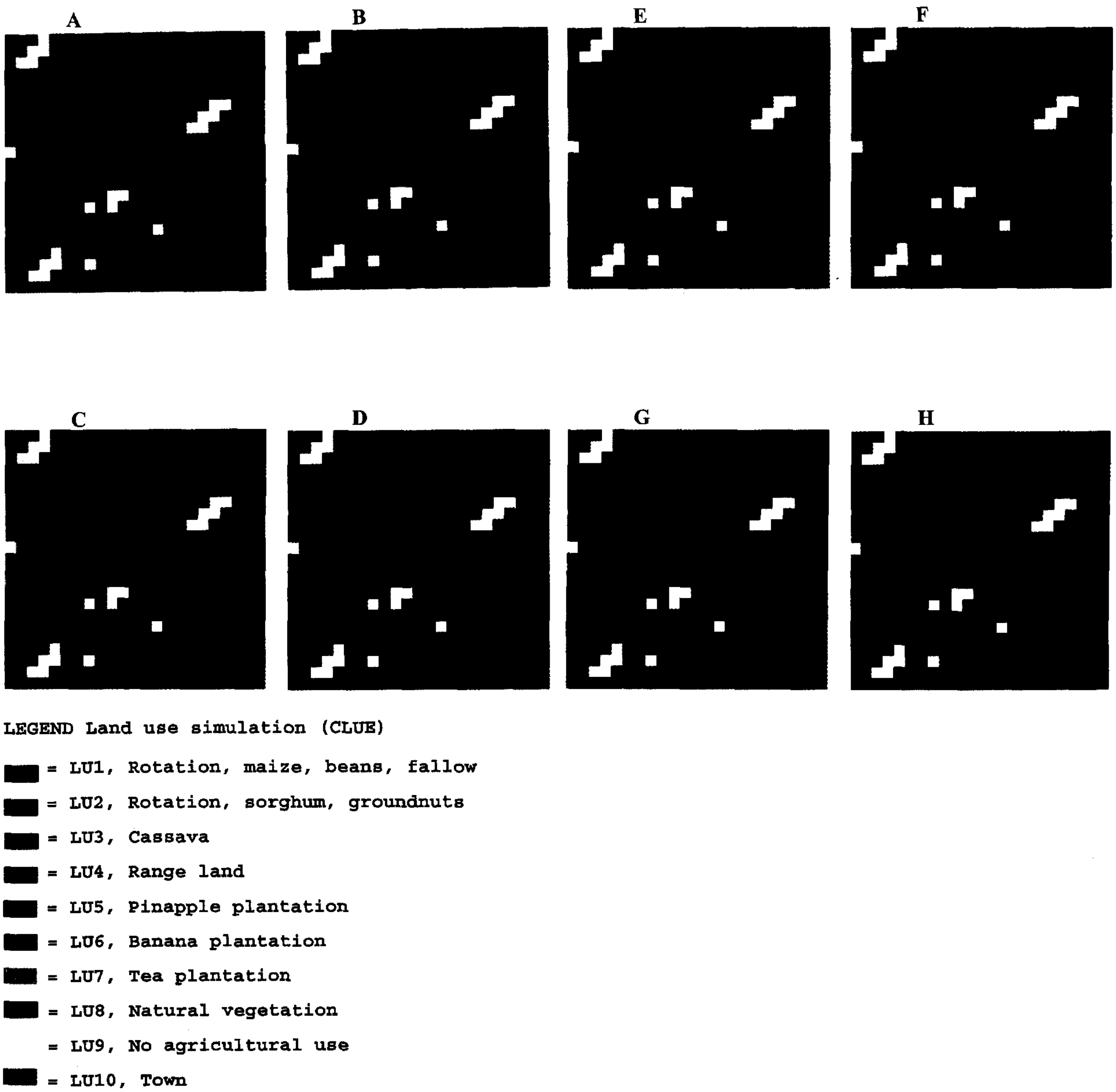


Fig. 5. Land use outputs of the described scenario.

- The population needs cattle for social purposes, so that cattle demand is also a function of population size.
- Another LU related decision is the social 'need' for natural vegetation for religious or recreational purposes. This 'need' leads to the strategy to strive to some natural vegetation.

f. The occurrence of crop specific diseases or pests in the area. The occurrence of a disease or crop specific pest in the region will cause a stagnation of further expansion of the land use with the diseased crop. As soon as a remedy for the disease or pest is available, a reintroduction or a further expansion of the crop follows.

8. Land use allocation module

After the regional objectives have been determined it is now evaluated at the local grid scale whether changes in land use are feasible. This evaluation is based on conservative assumptions, i.e. a land use conversion takes place only when the new land use gives a clear yield or value improvement. The simulation proceeds according to the following sequence:

a. The areas of concentration for each food and social land use types are determined by applying a flexible search window procedure. This window has a minimum size of four grids and a maximum of 22 by 22 grids. By using a given window size and a selected threshold value the land use concentration areas can be determined. The coordinates of these concentration areas are stored for all food producing and socially related land use types (LU1, LU2, LU3, LU4, LU8, LU10).

b. Next, another search procedure is started based on the infrastructure. When the lay out of the infrastructure has been determined by a search procedure, the concentrations of commercial land use types (LU5, LU6, LU7) along the infrastructure are counted and stored separately.

c. Subsequently, it is determined what the regional land use objectives are for the region as a whole.

d. After the land users decision on how many grids of certain LU types are preferred, two different land use allocation schemes (Fig. 4) are applied. For food crops (LU1, 2, 3, 4) an allocation procedure causing spiral wise growth of land use concentration regions is applied, while commercial LU types (LU5, 6, 7) are allocated along the existing main infrastructure as the products of these LU types need to be transported outside the region. The remaining LU types, natural vegetation (LU8), bare lands unsuitable for agriculture (LU9) and towns (LU10) are allocated by both allocation schemes.

At the *local* grid scale the following criteria play a dominant role in the final land use change decision:

LAND-USE-CHANGE = f(current land use + desired land uses + LU values + LU suitabilities + diseases + relative geographical position to infrastructure + minimum economical age)

e. The occurrence of pests and diseases. As a disease takes time to spread spatially the effects of a disease gradually migrate the infrastructure network and contact contamination through the region. Occasionally, local areas are spared from the disease.

f. Suitability of the individual grids for the different LU types. The grid suitability for a potentially new crop is checked. Only land uses for which the grid under consideration has a at least a fairly suitability may be allocated to this grid.

g. Position of grid cell with respect to concentration areas and infrastructure. Position of a grid with respect to concentration areas and infrastructure can strongly influence what kind of land use may be practised. Commercial land uses need a good infrastructure to transport its product to the (inter)national market, while food producing land use types are not bound to the main infrastructure.

h. Existing land use and the proposed new land use are compared and evaluated. The 'value' of the actual and proposed land use are determined and compared. This 'value' depends on the yield level, the applied land use strategy and the grid biophysical suitabilities for the different land uses.

i. The minimum economical age of existing land use. A land use type with perennials once established needs a minimum amount of time to start producing and gain value. It is assumed that no land use is changed as long as it has not reached its minimum economical age. During the LU allocation procedures each grid unit is evaluated individually.

9. Model outputs

For each simulated month or year the regional land use and coverage pattern can be stored. Coverage is a function of LU type, stage of growing season and local biophysical suitability. Because the land cover and use are still strongly related within this prototype, only land use types will be given as output in the simulation example. Land cover outputs can be derived from Table 2 and Fig. 1 and Fig. 6.

10. A scenario example

In order to demonstrate CLUE's potential we now discuss a theoretical simulation scenario run over several decades with all land use controlling factors as described above. Within the initial region (Fig. 2) all ten land use types are found, the ages of the land use types for each grid are old enough to pose no limitation in the final change decision. The simulation starts with a food security strategy resulting in a region with the four food producing land uses (Fig. 5a). As long as the area produces sufficient food there is room to allow the socially controlled land uses, natural vegetation and cattle to expand. In due time, technology level increases causing a concurrent change in food habits and values as expressed in the second land use strategy (Table 3). The effects of this change in strategy is an increase in LU3 at the cost of LU2 (Fig. 5b and c). During the entire simulation the demand for cattle and natural vegetation continues to exist and is met as long as the food security is guaranteed. A subsequent change in land use strategy causes the gradual introduction of the first commercial land use types within the region along the existing infrastructure (Fig. 5d and e). As these commercial land use types have higher yields than the food producing land uses, more space becomes available for range land and natural vegetation (Fig. 5e and f). After a while a disease in one of the commercial land use types (pineapple, LU5) is introduced. While the disease spreads in the region, pineapple production comes to a halt and other commercial land uses like tea and banana take over (Fig. 5g). Without the introduction of this pineapple disease, tea, which has an assumed lower output (value) than pineapple, would not have been introduced within the region. Meanwhile, the total area of commercial land use increases to the detriment of subsistent land use. Finally, the land use strategy is completely focused on commercial land uses causing a further increase of these land uses in the region (Fig. 5g). After several years a remedy for the pineapple disease is available, causing a reintroduction of pineapple plantations within the area (Fig. 5h). Remote areas, not directly assessable by the main infrastructure (Fig. 2), remain under food producing land uses. These areas are gradually converted into grazing areas as the grown population requires more and more cattle (both food and social requirements). At the end of this simulation (Fig. 5h) a pattern with several land use zones (a LU1, LU2, LU3, LU4, LU6 and LU7 zone) have developed within the region as a result of the combined effects of local suitabilities, infrastructure and the use of concentration regions in the allocation procedures.

The individual grid cell evaluation shows that certain grids are best suitable for one LU only while other grids are suitable for various LU types. As a result, some grids hardly ever show a change in land use (a kind of land use niche) while other grids demonstrate frequent land use changes strongly related to changing regional and international conditions. Such spatial dynamics of

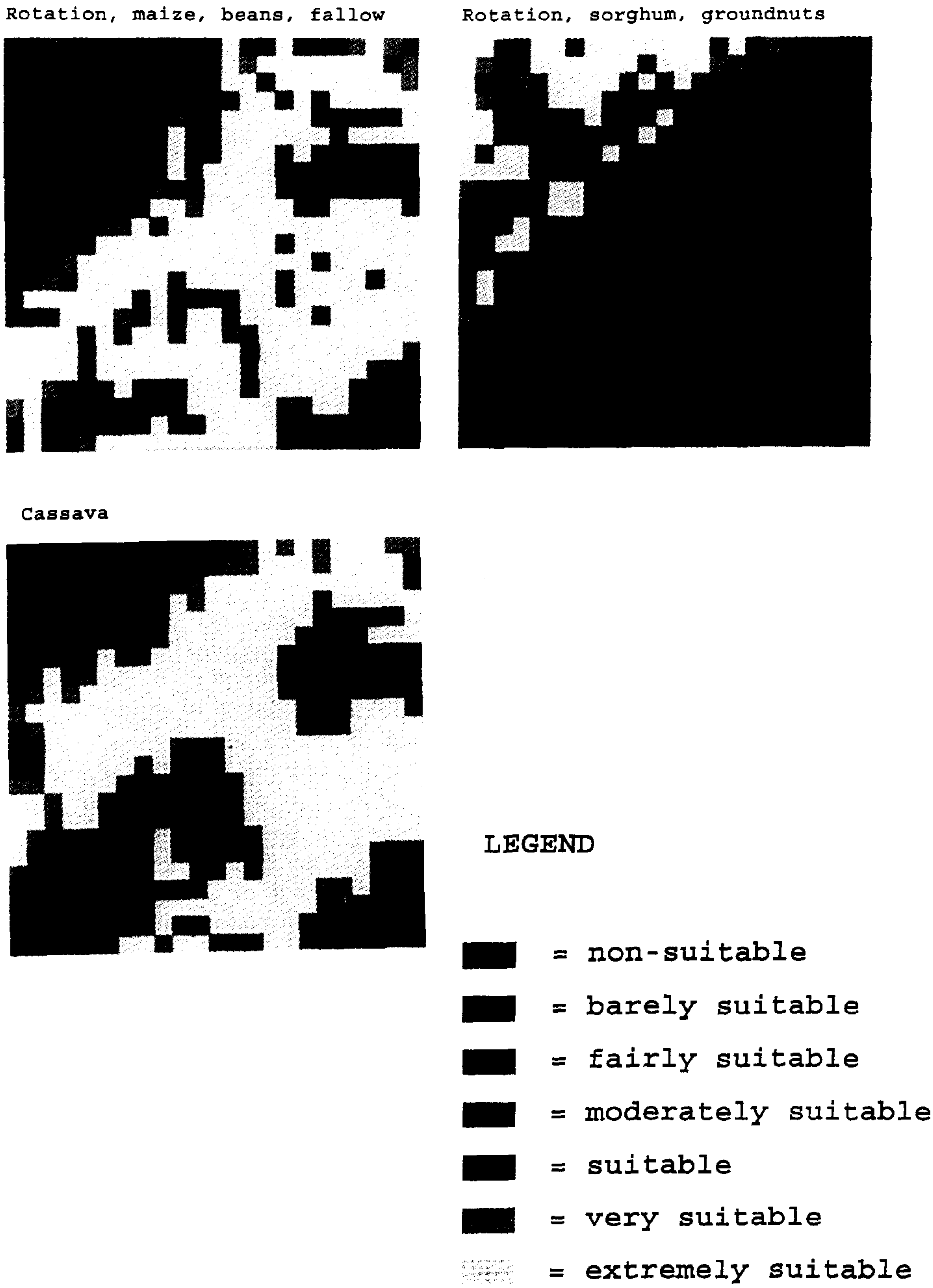


Fig. 6. Output of land suitabilities after the described simulation.

land use suggest a strong analogy with biophysical niches (Holling, 1992).

The effects of non-biophysical factors are illustrated by the observation that land use zones are not always situated on the biophysically most suitable areas for the grown crops (comparison of Fig. 5h and Fig. 6). This observation suggests that land use zones and agro-ecological zones not necessarily coincide. Although the higher suitability grids dominate a land use zone, the LU1, LU2, LU3 and LU4 zones are also found on grids with suitability ratings of barely to extremely suitable. Apart from land use zones a kind of 'land use niches' can also be observed. Especially within the food producing land use areas such niches are evidently related to the combined effects of geographical position and local suitabilities.

Regional land use is strongly related to human demands. As a result of population and technology level increase the efficiency of land use has increased considerably and became strongly dependent on the high-yielding commercial land uses. This dependence creates a situation where a return to a regional food security is virtually impossible, due to the excessive populations size and the reduced suitabilities (carrying capacity) of the simulated region. The reduction in biophysical suitabilities of LU1, 2 and 3, the only three land uses for which a feed back mechanism for over use was incorporated within CLUE, are shown in Fig. 6. A comparison with the initial suitabilities in Fig. 1 demonstrates the long-term effects of none sustainable land use systems.

11. General discussion and conclusions

11.1. Model validity, sensitivity and tuning

Our aim in developing CLUE was to formulate a tool that is robust enough to include all major forces driving land use as well as a sufficient diversity of biophysical conditions and land use types in order to construct and evaluate possible land use change scenarios. The described scenario served as a first test to identify (a) possible patterns and trends of land use change, and (b) important gaps in the conceptual model underlying CLUE.

The results of the initial scenario run show that the model does not suffer from biased or skewed distributions of land use and that 'plausible' patterns emerge.

At this stage our aim was not to simulate a known situation based on realistic population growth and technology development figures, although the technical quantitative and qualitative input/output coefficients of each land use have been based on documented patterns. Once realistic inputs are applied, a careful calibration of the model becomes necessary. An effective tuning can be done by matching historical land use pattern and production data with known population sizes and infrastructure. A calibration strategy should be aimed at preventing famine conditions occurring in the simulation runs unless these occurred also in reality.

Another way to tune or even validate a realistic version of CLUE might be found in the land cover characteristics and dynamics as measured by satellite imagery. Land cover is then assumed to reflect land use and its related inputs combined with annual fluctuations in biophysical characteristics (climate). The application of satellite images and/or aerial-photographs might thus strengthen tuning and/or validation attempts of CLUE, although it will never be able to replace the data need for biophysical land qualities and quantities combined with land use practises, production quantities, population size or density and infrastructure.

A sensitivity/uncertainty analysis of CLUE is only possible for a specific selected and tuned scenario. Such a realistic scenario would allow a first estimation of the input variability and reliability both needed to perform meaningful Monte Carlo simulations and model analysis.

11.2. CLUE applications

In the first model version of CLUE, general land use principles and drivers were translated into example assumptions to demonstrate their possible effects and interactions. The relationships and functions applied were not described in detail since land use prediction was not our main aim. It is obvious that a model with as many uncertain (qualitative) relationships as CLUE will never attain a realistic predictable value without much more quantitative research on the underlying mechanisms of land use changes and strategies. Despite these uncertainties, CLUE simulations can give insight into the complex interaction of the various biophysical and human drivers of land use, and prevent 'impossible' predictions. An example is the evaluation of sustainability concepts and scenarios which can be applied and evaluated by CLUE for any selected region and scenario. By introducing various feedback loops for over-use, long-term effects of land use systems can be made clear. This is especially important within the current strategy to strive to more sustainable land uses (Fresco and Kroonenberg, 1992).

On a regional scale CLUE like models can be applied to evaluate proposed land use options. CLUE can serve as a check of planned land uses or land use policies and can visualise regional impact and interactions of possible land uses.

CLUE accommodates the three basic kinds of land use changes, land use expansion (e.g. Amazonia), intensification (SE Asia) and contraction (European Union). This flexibility indicates that the CLUE approach can contribute to a better understanding of land use conversion and changes in time. Within current global change research it has been attempted to evaluate potential future effects of climate change on agriculture (Rosenzweig et al., 1993; Rosenzweig and Parry, 1994), by combining theoretical crop models and climate change models. Both model types are based on biophysical processes only, which limits the value of such exercises considerably from a land use point of view. Initial CLUE simulations demonstrate beyond doubt that land use changes are not controlled but only influenced by biophysical processes, and give due weight to the role of demographic and economic factors.

Any prediction about future land uses or agriculture without incorporating human behaviour and decisions will never attain a realistic predicting value. CLUE or similar approaches could contribute to directing global change research by elaborating the commonly applied feed back mechanisms between land use (cover) and climate, with land use feed back links with demographic and economic systems. We believe that only such an integrated approach might achieve a more complete and realistic insight in the complex real world systems.

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