Modelling land use changes and their temporal and spatial variability with CLUE.

A pilot study for Costa Rica.

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CONTENTS

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The research was carried out at the Department of Agronomy Wageningen Agricultural University and at National Institute of Public Health and Environmetnal Protection, Bilthoven.
The Dirección General de Estadística y Censos (DGEC) in Costa Rica and the field team of the Programma Zona Atlantica (PZA) at Guapiles of the joint programma of CATIE, MAG and the Agricultural University Wageningen have been helpful in providing information and agronomic census data of 1973 and 1984.

Summary:
Integration problems related to modelling land use dynamics in integrated climate change models such as the Integrated Model to Assess the Greenhouse Effect (IMAGE 2.0) (Alcamo et al., 1994) have been investigated for Costa Rica. These problems can be summarized as (I) dynamics of natural vegetation vs. agricultural use, (II) Spatial scales, global vs. regional, (III) temporal scales, rapid agricultural changes vs. relatively slow climate changes, (IV) Idenfication of relevant land use drivers. First a sensitivity analysis of the Terrestrial Vegetation Model (TVM) in IMAGE 2.0, which determines potential land cover for natural ecosystems and potential productivity for agro-systems, was made. This analysis demonstrated that the TVM is principally a robust model which is not very sensitive for climate input variability. Much observed output variability is related to model parameters. A first tentative comparison of maize, rice and pulses yield potentials and their distribution in Costa Rica during 1973 and 1984, suggests that the assumption that the two are related, as assumed in the Land Cover Model (LCM) in IMAGE 2.0, has only limited global validity.
To study the actual spatial and temporal Costa Rican land use dynamics in more detail a nested scale analysis was made of Costa Rican land use and cover in 1973 and 1984. Spatial distributions of potential biophysical and human land use/cover drivers 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 have changing model fits and varying contributions of biophysical and human factors, indicating a considerable scale dependence of the land use/cover patterns. The observation that for both years each land use/cover type has its own specific scale dependencies, suggests a rather stable scale dependent system. The nested scale analysis of the Costa Rica land use/cover confirms that land use/cover heterogeneity is, like ecosystem and landscape heterogeneity, a multi-scale characteristic which can best be described as a nested hierarchical system. The nested scale analysis gave also insight into the relevant land use drivers and their scale dependence. To support future modelling effects of land use dynamics based on land use drivers, a dynamic framework to simulate Conversion of Land Use and its Effects (CLUE) was developed. CLUE attempts to simulate land use conversion and change in space and time as a result of interacting biophysical and human drivers.
A dynamic geo-referenced land use/cover model (CLUE-CR) which simulates simultaneous local, regional and national land use/cover changes in Costa Rica was developed. 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 constrains. 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.

CHAPTER 1:
General Project outline

1.1 Project background

Human activities influence and alter land covers. Recent research indicates that human-induced conversions (e.g. deforestation) and modifications (e.g. changing land use management such as fertilizer use and irrigation practices) of land cover have significance for the functioning of the earth system (Houghton et al., 1991; Turner et al., 1994). The influence of these land cover changes becomes globally significant through their accumulative effects. Most recent land cover modification and conversion is clearly driven by human use, rather than natural change (Skole and Tucker, 1993). In general, land use is viewed to be constrained by biophysical factors such as soil, climate, relief and vegetation. On the other hand, human activities that make use of or change land attributes are considered as the proximate sources of land use/cover change. Interpretations of how such land use/cover driving forces act and interact is still controversial, especially the assessment of the relative importance of the different forces and factors underlying land use decisions in specific cases. An illustrative case study of land cover changes (Turner et al., 1993) demonstrated that land use changes that drive land cover change are tied to numerous human factors, some of which may be spatially distant from the area affected, leading to the conclusion that the processes involved in land cover and land use change operate across many spatial and temporal scales. An understanding of land use/cover change would thus be factually incomplete and lead to inadequate projections if its causes were sought only in the proximate sources of change or in forces operating within the region and within the time-frame studied. The observation that causal links identified at one scale may not appear at other scales and v.v. is called the scale effect. Therefore, any attempt to reconstruct or link human and biophysical drivers of land use/cover can thus only be successful when this effort is carried out at various different scales.

Summarizing, a major pressing issue associated with global environmental change is its detailed effects on land use and, conversely, the impact of land use on the carbon cycle and atmospheric CO_2 processes. Much knowledge has already been gathered in various related fields, but integration lags behind in several aspects:

(I) Natural vegetation vs. agricultural land use: Considerable progress has been made recently in predicting global vegetation patterns on the base of plant physiology and climate and linking these with GCM, in particular in BIOME (Prentice et al 1992). At present, however, these models are not very able to deal with regions where natural vegetation has been replaced by varying agro-ecosystems. Further progress in linking land use and global change is hampered by the inexistence of a world-wide data base on land use.

(II) Spatial scales: global vs. regional: The fit between predicted and actual patterns of vegetation in models such as that of Prentice et al., (1992) is better at smaller spatial scales, partly as a result of differences in human activities such as agriculture. But there is a lack of methods to link up global models with agricultural variables available at regional scales only. Some initial studies have been carried out in modelling the impact of global climatic change on agriculture on a regional scale, especially in sensitive areas with marginal agriculture (Parry et al., 1988). In view of the continuing growth rate of the area under agricultural land use, in particular in the (sub)humid tropics, an adequate assessment of determinants of land use is essential. A first step may be to find ways to "zoom in" into greater detail and smaller areas and describe the factors determining land use accordingly. This would link up with other efforts to regionalise global change models that are currently undertaken.

(III) Time scales of processes affecting agriculture: Global-scale models for simulation of the effect of climatic change on agriculture depict future output of agricultural systems mainly on the base of temperature and precipitation and CO_2 as variables. However, sustainable land use refers to a much more complex set of parameters than climatological and atmospherical data alone. In order to assess the impact of climatic change we must gain a better understanding of sources of variability affecting agro-ecosystems. These fall into two broad categories: rates of change of **natural** processes with time scales extending from $10 - 10^6$ years, and variability inherent to **agricultural** land use usually measured on a seasonal, annual or decade basis. Dynamic models are required that may accommodate both rapid human population growth and concomitant land use, as well as situations where the rate of environmental change exceeds that of natural vegetation and crop adjustment.

(IV) Land use drivers: In the IMAGE 2.0 model, the land use module is based on the attribution of single or uniform land use to individual grid (0.5°* 0.5°) cells. For obvious reasons, no account can be taken of variability of land uses and crops and the distribution of yields within grid cells. Land suitability for crops is based on the FAO agro-ecological zoning methods, disregarding the fact that population pressure may lead to overutilization of unsuitable lands. As a result, yield estimates are necessarily very crude and insufficiently based on known distributions of crop yields. A related issue is the fact that there is still very little insight in the driving factors of changing land use. Their relative importance, in particular the contribution and interactions of socio-economic (demographic, infrastructure, markets) and biophysical factors is still unclear. A case study of main driving factors in a rapidly changing situation would also allow the development of simple indicators for further incorporation in global models.

1.2 Project Research Objectives

The project "*Elaborating of land use and related factors and their temporal and spatial variability into IMAGE 2 - a pilot study.*" aims to contribute to a better integration of land use and its driving variables in the global IMAGE 2 model through a case study of Costa Rica. The four named integration lags were therefore investigated for Costa Rica. The research started with an extensive analysis of the IMAGE 2.0 model performance for the 18 relevant grids representing Costa Rica (Chapter 2). This sensitivity analysis was followed by an in depth analysis of both spatial (Lag II) and temporal (Lag III) dynamics of Costa Rica land use (Chapter 3). Furthermore it was attempted to identify and quantify potential land use drivers for Costa Rican land use using a nested scale analysis (Lags I and IV). Because no existing land use models are able to simulated land use changes as a functions of various land use drivers (Lag IV) a new conceptual framework (CLUE) was constructed to support future modelling efforts (Chapter 4). This framework was applied for Costa Rica based on 1973 and 1984 data (Chapter 5). Finally the conclusions based on the project results are given in Chapter 6.

CHAPTER 2:

A model analysis of the terrestrial vegetation model of IMAGE 2.0 for Costa Rica.

By: A. Veldkamp & G. Zuidema

2.1 Introduction

The Integrated Model to Assess the Greenhouse Effect (IMAGE 2.0) is a multi-disciplinary and integrated model designed at the National Institute of Public Health and Environmental Protection, the Netherlands, to simulate the dynamics of the global society-biosphere-climate system (Alcamo et al., 1994). The objectives of the model are to investigate linkages and feedbacks in the system, and to evaluate consequences of climate policies. Dynamic calculations are performed with different time steps (1970-2050), on different geographical scales, depending on the sub-model (ranging from one day to five years and 0.5° latitude x 0.5° longitude to world region respectively).

IMAGE 2.0 links and integrates both complex models and Geographic Information Systems (GIS). One of the main dangers of integrated computer modelling as done with IMAGE 2.0 is that unskilled users may uncritically accept simulation results and assume that such a complex model performs adequately. Even experts may accept simulated results without sufficient validation. Model errors of integrated model-GIS systems are usually related to both the GIS data as the model relations (Burrough et al., 1993). Model predictions can thus be affected by uncertainty and errors in the geo-referenced data as well as in the applied model functions and boundary/threshold conditions. The most direct and effective way to analyze these potential error sources is a model analysis. As extensive Monte Carlo simulations with IMAGE 2.0 would require years to complete, it was decided to make a model analysis for the different sub-models (Alcamo et al., 1994). A first analysis carried out for the Atmospheric Composition sub-model showed the existence of a strong contribution to output variability by model parameters (Krol et al, 1994).

Another relevant sub-model in IMAGE 2.0 is the Terrestrial Vegetation Model (TVM) which determines potential land cover for natural ecosystems and potential productivity for agro-systems (Leemans and van der Born, 1994). A sensitivity analysis of this sub-model for the whole global data set would still require an enormous computing effort. It was therefore decided to limit the first model analysis to a country with sufficient different climatic environments and sufficient data availability. Because the global climate data set is relatively more reliable for higher latitudes than for lower latitudes (Leemans and Cramer, 1991) a lower latitude country was selected, Costa Rica. This paper describes the model analysis of the TVM for the 18 Costa Rican grid cells (0.5°x 0.5° latitude-longitude) (Fig. 2.1).

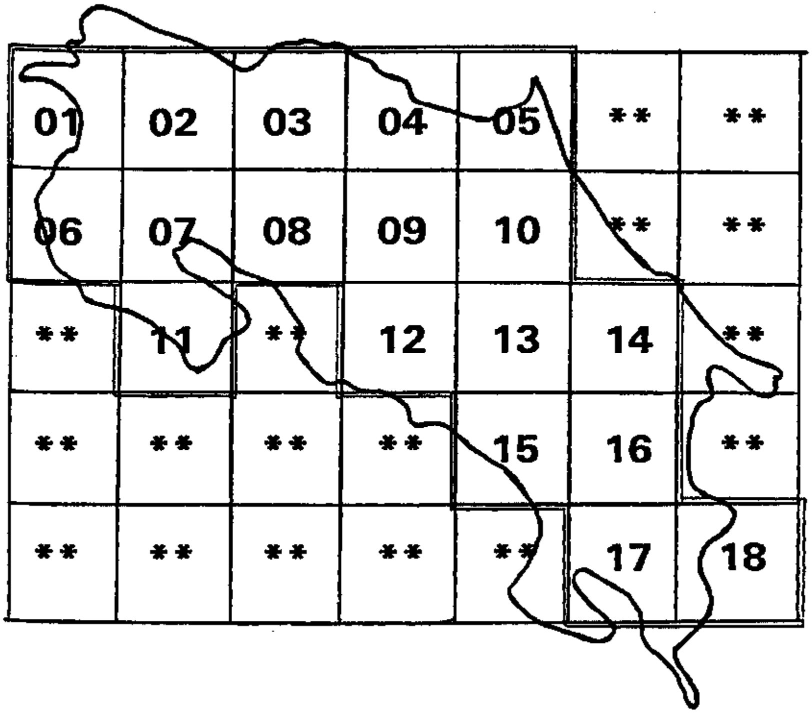


Fig. 2.1 **Location of IMAGE 2.0 grid cells and their individual identification no. in Costa Rica.**

2.2 Climate and crops in Costa Rica

Costa Rica's topography is dominated by a central spine of mainly volcanic mountains stretching from northwest to the southeast. Exceeding 2.500 m at numerous places in a country only 260 km wide at maximum, the mountains divide the country into two distinct zones dominated by Atlantic and Pacific weather systems, creating tremendous variation in temperature and precipitation regimes (Herrera, 1985). Costa Rica contains 14 of the 31 of the world's tropical bio-climatic zones (Holdridge, 1967; Gómez 1986). Soils, in addition to altitude and climate, influence the natural vegetation and the human land uses that replace it. Mountainous regions above 1000 m are generally cool and temperate, with abundant and moderately seasonal rainfall (2-5 m/yr). Extensional coastal plains lie to the east and west of the mountains. In the Atlantic and southern Pacific lowlands, rainfall is high (2-7 m/yr) and relatively aseasonal. The northern half of the Pacific coastal plain forms a distinct, markedly drier (1-2 m/yr) region, where precipitation is more seasonal than in the rest of the country. Nowadays most of the natural vegetation in Costa Rica has been replaced by human land use (DGEC, 1987). Each decade the DGEC composes an agrarian census database containing detailed crop yields for each canton and province in Costa Rica. The 1973 and 1984 crop distributions for rice, maize and beans were aggregated into the (0.5°x 0.5°) grid cells to allow a qualitative comparison with the TVM calculated potential yield trends.

2.3 Terrestrial vegetation model of IMAGE 2.0

The Terrestrial Vegetation Model (TVM) of IMAGE 2.0 simulates the potential distribution of vegetation and major crops. A main assumption within the TVM is that there is a strong linkage between climate, vegetation and crop distribution (Leemans, 1992; Leemans and van den Born, 1994). Another important model assumption is that the vegetation and crop distribution exist under equilibrium conditions for completely rainfed conditions on well drained soils, thus excluding irrigated agriculture and waterlogging. For natural ecosystems their potential is corresponding to a fully developed and not degraded system, while for crops it is defined as those conditions adequate for obtaining an economically feasible yield. The TVM is implemented with a high-resolution (0.5°x 0.5° latitude-longitude) gridded climate data base (Leemans and Cramer, 1991). Climate is described by 'normal' data of a station or region based on a long term average of weather records. Such climatic normals are essential to describe the interactions between climate and other biosphere components such as vegetation and crops. Within IMAGE 2.0 the monthly patterns of temperature (mean, minimum and maximum), precipitation (mean and range) and cloudiness are used. A water balance model yielding the daily available soil moisture for plant growth is used in combination with a temperature regime to define the characteristics of the growing season. The length of growing season is defined as that period during the year when warmth and soil moisture are adequate for vegetation/crop growth. Besides length of growing season, monthly precipitation and temperature of the coldest and warmest month are determined. Effective temperature sums are computed by using the interpolated daily temperature values. Further several climatic crop requirements are defined for the 16 selected crop types of which some are listed in Tab. 2.1. If a crop can grow in a certain grid cell, its productivity is determined using a simple photosynthetical model based on the crop models of de Wit (1965) and adapted from the specific approach by FAO (FAO, 1978). Photosynthesis is governed by the total amount of irradiance, which is dependent on latitude and cloudiness fraction during the growing season and is also a function of temperature. Water-limited yields are thus calculated for all crops as listed in Tab. 2.1. After these potential yields are calculated some crops are aggregated into economic crop groups, roots (potatoes and cassava), Sugar crops (sugar cane and sugar beet) and Oil crops (Oil palm, sunflower, rapeseed and cottonseed). For each economic group the highest yield potential is used. More specific information is given by Leemans and van den Born (1994). These economic crop groups are used in the Land Cover Model (LCM), another sub-model of the terrestrial environment system of IMAGE 2.0 (Zuidema et al., 1994), together with a demand for agricultural products to calculate actual land cover.

Tab. 2.1 Climate crop requirements for the 16 major crop varieties in the TVM.
MTR = temperature of the coldest month (°C);
MR = moisture index (ratio of annual AET and PET);
Final crop group = Economic crop groups.

Crops	MTR	MR	Final crop group
Temperate maize	-20< <15	-	Maize
Tropical maize	≥ 5	-	Maize
Rice	≥-7.5	≥0.95	Rice
Spring wheat	< 5	-	Wheat
Winter wheat	< 10	-	Wheat
millet	≥-25	<0.95	Millet
Potatoes	< 15	-	Roots
Cassava	≥ 10	-	Roots
Pulses	< 20	-	Pulses
Sugar beet	< 15	-	Sugar
Sugar Cane	≥ 10	-	Sugar
Soy beans	< 20	-	Oil
Oil palm	≥ 10	-	Oil
Sunflower	< 10	-	Oil
Rapeseed	< 10	-	Oil
Cottonseed	≥-5	-	Oil

2.4 Materials and methods

A standard model analysis consists of performing a sensitivity analysis in order to gain more insight in the crucial aspects of the model and its data. A common and effective model analyzing technique is the Monte Carlo method using Latin Hypercube Sampling (Janssen et al., 1990). The IMAGE 2.0 standard climate data set is derived from an extensive interpolation exercise of many meteorological stations. In case of Costa Rica only one national meteorological station (San José) was included within this interpolation exercise, making the standard IMAGE 2.0 data set less suitable for a sensitivity analysis. Based on more than one hundred Costa Rican meteorological stations (Herrera, 1985; Gómez, 1986) new climatological data and their variability were calculated. The model inputs and outputs were statistically analyzed using the SAS software package.

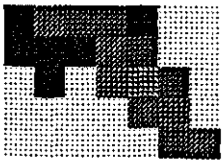
Inputs

The available Costa Rican meteorological stations (Herrera, 1985; Gómez, 1986) were grouped in the IMAGE 2.0 grids (0.5°x 0.5° latitude-longitude, Fig. 2.1). The long term mean monthly precipitation and mean monthly temperature data were used to determine the variability within each grid unit. The amount of stations within a grid cell ranged from 2 to 12. These monthly precipitation and temperature data, their distributions and correlations were used for Monte Carlo sampling with the latin hypercube technique. This technique uses a stratified way of sampling from the separate source ranges, sampling each range only once (Janssen et al., 1990).

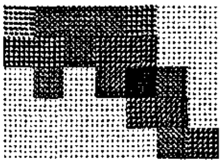
50 precipitation (mm) and 50 temperature (°C) input combinations were sampled, each consisting of 12 monthly temperatures and 12 monthly precipitation data for all 18 grid cells. The two different input data sets were combined and used for simulation with the TVM of IMAGE 2.0, resulting in 50 * 50 = 2500 runs for each grid cell. Another standard input data set in the TVM describes monthly cloudiness (%). As the cloudiness data in Costa Rica are limited and of uncertain quality, no reliable statistical analysis could be made to support useful monte carlo simulations, consequently the standard IMAGE 2.0 cloudiness values were used.

Statistical analysis of the Costa Rican climate data demonstrated strong correlations between many data. An analysis of their variance and their interrelationships with ANOVA and factor analysis (principal component extraction and varimax rotation) indicated that the climatic variability (> 95% of total variance) of both temperature and precipitation can be sufficiently described by only three independent climatic variables, mean temperature in May (TMAY), mean precipitation in January (PJAN) and mean precipitation in October (POCT).

Input variable, TMAY

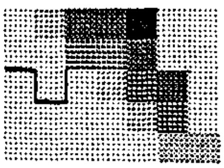


Mean values for each individual grid (°C), Min = 14.8 to Max = 28.2 °C

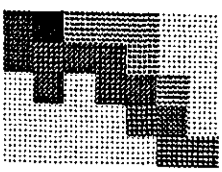


Coefficient of variance for each individual grid (CV), Min = 4.2 to Max = 9.8 %

Input variable PJAN

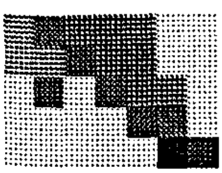


Mean values for each individual grid (mm), Min = 4 to Max = 372 mm

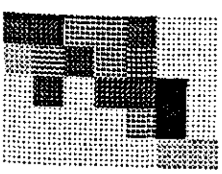


Coefficient of variance for each individual grid (CV), Min = 19.2 to Max = 63.3 %

Input variable POCT



Mean values for each individual grid (mm), Min = 210 to Max = 664 mm



Coefficient of variance for each individual grid (CV), Min = 8.7 to Max = 34.0 %

Fig. 2.2 **Distribution of Means and Coefficient of variance (CV) of the Input variables TMAY (Mean temperature in May), PJAN (Mean precipitation in January) and POCT (Mean precipitation in October).**

Tab. 2.2 Descriptive statistics (Means, Standard deviations, Minimum, Maximum, Intra and Inter grid variance and Coefficient of variance) of input and output variables.

Variable	N	Units	Mean	Std Dev	Min.	Max.	Intra Grid variance	Inter Grid variance	Inter/Intra var. coeff.	Coefficient of variance %
INPUTS										
TMAY	46436	°C	24.8	35.5	12.2	31.7	274.1	1006.3	3.67	14.29
PJAN	46436	mm	135	119.4	0	534	2786.9	11704.1	4.20	88.02
POCT	46436	mm	410	141.8	99	783	7110.6	13273.2	1.87	34.58
OUTPUTS:										
LENGTH	46436	days	349	28.0	259	365	178.7	619.7	3.47	8.03
TEMP	46436	°C	24.0	34.5	11.8	30.3	221.2	989.3	4.47	14.36
RICE	46436	ton/ha	942	9.3	590	1100	25.6	63.2	2.47	9.93
MAIZE	46436	ton/ha	1639	16.0	1210	2110	54.6	205.4	3.76	9.76
MILLET	46436	ton/ha	461	51.0	0	1320	898.1	1745.1	1.94	110.75
PULSES	46436	ton/ha	129	25.5	0	870	237.9	424.8	1.79	196.97
ROOTS	46436	ton/ha	1875	17.7	1400	2190	56.5	263.4	4.66	9.46
OIL	46436	ton/ha	1100	10.9	650	1280	35.9	86.2	2.40	9.98
SUGAR	46436	ton/ha	5357	87.8	1820	6120	534.8	7323.0	13.69	16.40

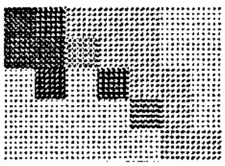
The suitability and validity of these three independent input variables is also supported by the observation that they are able to explain up to 98% of the model output variability by multiple regression modelling. Grid means and coefficient of variance (CV) values of these three input variables are given in Fig. 2.2 and summarized in Tab. 2.2. The maps in Fig. 2.2 display the range of grid values between the minimum and maximum values. For each individual variable 15 equal interval classes were made ranging from its minimum (almost white) to its maximum (almost black) leaving many classes empty. The individual classification of each variable makes the given maps not directly comparable, but they illustrate the different grid values for Costa Rica.

Outputs

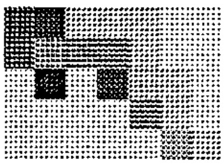
The 2500 simulation runs of the TVM sub-model yielded the following output variables: Potential vegetation class, length of growing season (LENGTH), mean temperature of growing season (TEMP), water-limited yield levels for: rice, maize, millet, pulses, roots, oil and sugar crops. For each output variable descriptive statistics (see Fig. 2.3) and ANOVA were carried out in order to determine the inter and intra grid variances (Tab. 2.2). Regression was applied to model the output variables variability by the three independent input descriptive variables TMAY, PJAN and POCT both on grid and national level (Fig. 2.3). The Costa Rica grid maps in Fig. 2.3 indicate the range of grid values for Regression model fits (R^2), Coefficient of variance (CV) and output means. The minimum (almost white) and maximum (almost black) values are also divided into 15 equal interval classes, meaning that apart for the R^2 maps (all ranging from 0 to 100%), the maps in Fig. 2.3 are not directly comparable.

Fig. 2.3 Distribution of model fits of multiple regressions (see listed models), Coefficient of variance (CV) and means of calculated model outputs for Costa Rica Grids, LENGTH (Length of growing season, (units: days)), TEMP (mean temperature of growing season (units: °C)) and potential waterlimited yield levels (units: ton/ha) for Rice, Maize, Millet, Pulses, Roots, Oil crops and sugar crops.

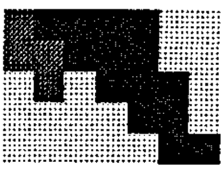
Model: LENGTH = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min = 0 to Max = 0.75.

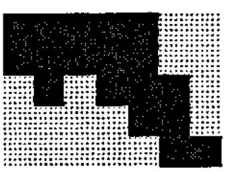


Coefficient of variance for each individual grid (CV), Min = 0 to Max = 8.9 %.

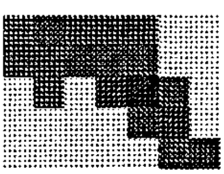


Mean values for each individual grid (days), Min = 297 to Max = 365 days.

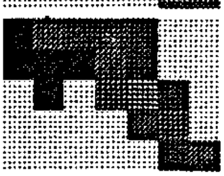
Model: TEMP = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min=0.96 to Max=0.98.

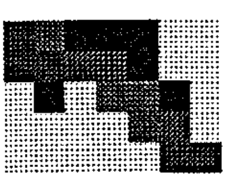


Coefficient of variance for each individual grid (CV), Min = 5.0 to Max = 8.8 %.



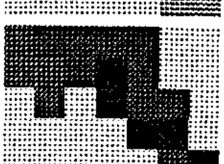
Mean values for each individual grid (^{0}C), Min = 14.1 to Max = 27.4 ^{0}C.

Model: RICE = TMAY + PJAN + POCT



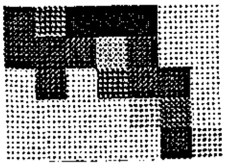
Model fit for each individual grid (R^2), Min = 0.61 to Max = 0.97.

Coefficient of variance for each individual grid (CV), Min = 1.9 to Max = 15.9 %.

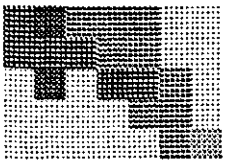


Mean values for each individual grid (ton/ha) Min = 799 to Max = 1062 ton/ha.

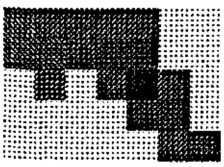
Model: MAIZE = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min = 0.19 to Max = 0.96.

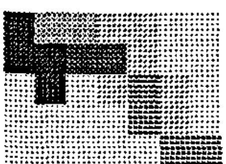


Coefficient of variance for each individual grid (CV), Min = 2.2 to Max = 6.6 %.

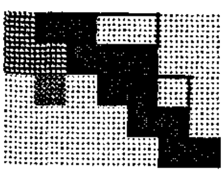


Mean values for each individual grid (ton/ha), Min = 1387 to Max = 1966 ton/ha.

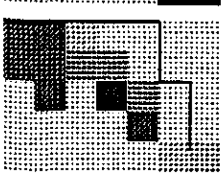
Model: MILLET = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min = 0 to Max = 0.92.

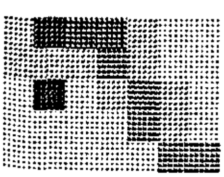


Coefficient of variance for each individual grid (CV), Min = 4.9 to Max = 625 %

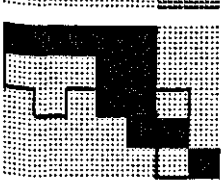


Mean values for each individual grid (ton/ha), Min = 0 to Max = 1127 ton/ha.

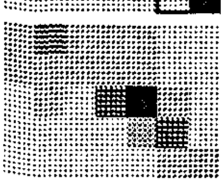
Model: PULSES = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min = 0 to Max = 0.79.

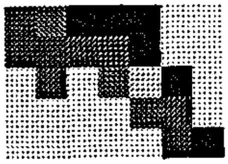


Coefficient of variance for each individual grid (CV), Min = 3.6 to Max = 700 %

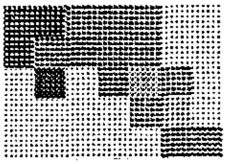


Mean values for each individual grid (ton/ha), Min = 0 to Max = 834 ton/ha.

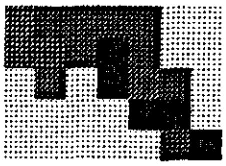
Model: ROOTS = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min= 0.06 to Max= 0.97.

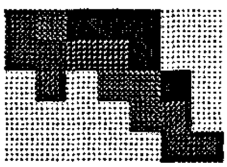


Coefficient of variance for each individual grid (CV), Min= 1.9 to Max= 6.1 %.

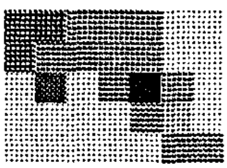


Mean values for each individual grid (ton/ha), Min= 1599 to Max= 2124 ton/ha.

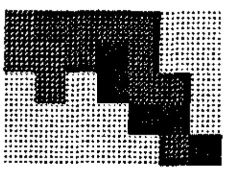
Model: OIL = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min= 0.61 to Max= 0.96.

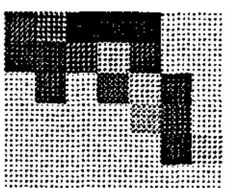


Coefficient of variance for each individual grid (CV), Min= 1.9 to Max= 16.6 %

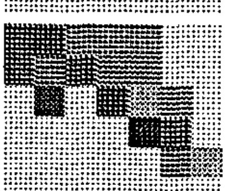


Mean values for each individual grid (ton/ha), Min= 933 to Max= 1239 ton/ha.

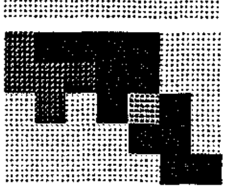
Model: SUGAR = TMAY + PJAN + POCT



Model fit for each individual grid (R^2), Min= 0.04 to Max= 0.96.



Coefficient of variance for each individual grid (CV), Min= 2.1 to Max= 8.1 %.



Mean values for each individual grid (ton/ha), Min= 2037 to Max= 5952 ton/ha

2.5 Results

Water-limited yields

All calculated output variables are given in Fig. 2.3. Wheat is not presented because all simulations resulted in yields of 0 ton/ha for all Costa Rican grid cells. A first comparison of the input and output data by correlation showed changing correlations for each output variable with the three input variables for the entire Costa Rica data set. More detailed insight can be obtained from comparing the trends in Fig. 2.2 and Fig. 2.3. The coefficients of variance (CV) of the input data (ranging from about 14% for TMAY, 35% for POCT to about 88% for PJAN) are usually much larger than the CV of the output data (Fig. 2.3 and Tab. 2.2), suggesting a certain robustness of the TVM. However this reduction of CV does not always occur. Especially millet and pulses outputs demonstrate considerably larger CV's, up to 700% for certain grids (Fig. 2.3). More detailed analysis of this high CV, revealed that in both cases (millet and pulses) this was caused by many yield failures (0 kg/ha) during the simulations. This is in both cases directly related to model criteria/thresholds concerning crop requirements (as listed in Tab. 2.1). Millet requires a moisture index < 0.95, a conditions not often met in the general humid climate of Costa Rica. Pulses on the other hand require a coldest month of < 20 °C a condition which is only found in the higher cooler grid cells. This strong model parameter related variability is confirmed by the observation that grids with higher mean water-limited yield levels for both millet and pulses (many years with a yield) have relatively low CV's. Another confirmation was obtained by regression modelling for each individual grid cell. These regression models attempt to explain calculated water-limited yield variability by the three independent input variables TMAY, PJAN and POCT. The model fits (R^2) are reported for each individual Costa Rica Grid (Fig. 2.3; and Tab. 2.3). The contributions of the three input variables to these regression models are listed in (Tab. 2.3) by + and - for each individual grid cell. It can be observed that the higher coefficients of determination (R^2) are related to lower output CV's. The output variable, length of growing season (LENGTH), has many grids with a coefficient of determination (R^2) of 0 because no variance can occur when all calculated length of growing seasons are 365 days (the whole year). For some grid cells a very low coefficient of determination is found for water-limited yield levels of crops which have a reasonable small CV. Examples are found in certain grids for Roots, Oil and Sugar crops. Detailed analysis of these grid cells shows that this was mainly due to the selection of different crops within the economical crop groups, Roots, Oil and Sugar. For one cool grid cell (no 13 in Fig. 2.1) a different sugar crop, sugar beet, was selected instead of the commonly selected sugar cane in the other Costa Rica grids. For this same grid cell potato instead of cassava was selected. The temperature related crop requirement parameter resulted in a considerable increase in the CV of the model outputs. A very similar observation applies for the oil crops were three different crops were selected for the Costa Rica grids causing changes in CV in the Oil crop outputs. These examples clearly indicate

Tab. 2.3 Multiple regression models (significance level of 0.05) of output variables (Coefficient of determination (R^2) and contributions of explaning variables (inputs)) for all 18 grids. model: OUTPUT = TMAY + PJAN + POCT.

Output	gridno: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Length	0.71	0.54	0.0	0.0	0.0	0.66	0.63	0.23	0.12	0.0	0.75	0.54	0.07	0.0	0.27	0.0	0.17	0.03
tmay	+	+	-	-	-	+	+	-	-	-	+	+	-	-	-	-	-	+
pjan	+	+	-	-	-	+	+	+	+	-	+	+	+	-	+	-	+	+
poct	+	+	-	-	-	+	+	+	+	-	+	+	-	-	-	-	-	+
Temp	0.97	0.97	0.97	0.97	0.98	0.96	0.97	0.98	0.98	0.98	0.97	0.98	0.96	0.98	0.98	0.98	0.98	0.98
tmay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
pjan	+	+	-	-	-	+	+	+	-	-	+	-	-	-	-	-	-	-
poct	+	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
Rice	0.87	0.68	0.97	0.97	0.97	.89	0.91	0.80	0.77	0.96	0.86	0.61	0.64	0.97	0.70	0.85	0.91	0.93
tmay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
pjan	+	+	-	-	-	+	+	+	+	-	+	+	-	-	+	-	+	-
poct	-	+	-	-	-	+	+	+	+	-	+	+	-	-	-	-	-	-
Maize	0.87	0.59	0.96	0.96	0.96	0.89	0.91	0.80	0.26	0.90	0.85	0.59	0.82	0.92	0.15	0.64	0.91	0.19
tmay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
pjan	+	+	-	-	-	+	+	+	+	-	+	+	+	-	+	-	+	-
poct	+	+	-	-	-	+	+	+	-	-	+	+	-	-	-	-	-	-
Millet	0.87	0.22	0.26	0.0	0.0	0.90	0.92	0.60	0.60	0.05	0.86	0.09	0.27	0.0	0.34	0.09	0.34	0.38
tmay	+	+	-	-	-	+	+	-	-	+	+	+	+	-	-	-	+	+
pjan	+	+	+	-	-	+	+	+	+	-	+	+	+	-	+	+	+	+
poct	+	+	+	-	-	+	+	+	+	-	+	+	+	-	-	-	+	+
Pulses	0.07	0.79	0.48	0.51	0.07	0.0	0.0	0.0	0.43	0.07	0.0	0.77	0.70	0.0	0.54	0.78	0.0	0.52
tmay	+	+	+	+	+	-	-	-	+	+	-	+	+	-	+	+	-	+
pjan	-	+	-	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-
poct	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Roots	0.88	0.69	0.97	0.97	0.97	0.90	0.92	0.80	0.75	0.97	0.86	0.61	0.06	0.96	0.71	0.85	0.92	0.95
tmay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
pjan	+	+	-	-	-	+	+	+	+	-	+	+	+	-	+	-	+	+
poct	+	+	-	-	-	+	+	+	+	-	+	+	-	-	-	-	-	-
Oil	0.87	0.69	0.96	0.98	0.97	0.89	0.91	0.79	0.76	0.96	0.86	0.61	0.64	0.96	0.70	0.85	0.91	0.93
tmay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
pjan	+	+	-	-	-	+	+	+	+	-	+	+	-	-	+	-	+	+
poct	+	+	-	-	-	+	+	+	+	-	+	+	-	-	-	-	-	-
Sugar	0.85	0.54	0.96	0.96	0.96	0.87	0.89	0.75	0.14	0.86	0.83	0.62	0.06	0.90	0.21	0.70	0.89	0.04
tmay	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
pjan	+	+	-	-	-	+	+	+	+	-	+	+	+	-	+	-	+	+
poct	+	+	-	-	-	+	+	+	-	-	+	+	-	-	-	-	-	+

Tab. 2.4 Overall regression models of the output variables (of 18 aggregated grids) with partial coefficients of determination (R^2) in (%), of input variables and grid-effects.
model: OUTPUT = TMAY + PJAN + POCT + GRID-effect

	TMAY (%) part.R^2	PJAN (%) part.R^2	POCT (%) part.R^2	GRID-eff(%) part.R^2	Total (%) R^2 model	unexpl totvar. (%)
Outputs:						
LENGTH	5.76	34.75	21.90	16.24	78.65	21.35
TEMP	98.59	0.00	0.03	0.80	99.42	0.58
RICE	40.50	7.60	5.30	24.67	78.07	21.93
MAIZE	57.51	11.34	5.81	8.78	83.44	16.56
MILLET	0.99	55.10	0.51	15.76	72.36	27.64
PULSES	65.09	0.06	0.34	8.89	74.38	25.62
ROOTS	27.98	8.27	5.41	52.11	93.77	6.23
OIL	39.58	7.49	5.31	24.78	77.16	22.84
SUGAR	11.38	4.93	2.34	75.86	94.51	5.49

that the role of model parameters and thresholds can considerably dominate the model output variability of the TVM.

When the Monte Carlo simulations are evaluated for Costa Rica as a whole, similar model effects can be observed (Tab. 2.4). The overall regression model fits are reasonable well ranging from 72% (Millet) to 99% (mean temperature during growing season), indicating the important contribution of both temperature and precipitation in explaining model output variability. A grid effect, independent of the three selected input variables, was determined by regression modelling. This grid effect ranges from 0.8% (TEMP) to 75% (sugar) of the total output variability. This grid effect can be interpreted as the not evaluated effect of cloudiness but can also be attributed to the model parameters used for the selection of crops for the economical crop groups. The latter effect seems to be most plausible explanation for the observed effects in Roots and Sugar variability. This effect could also explain the detected differences in the calculated inter/intra grid variance coefficients (Tab.2.2).

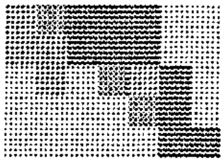
Potential vegetation

Potential vegetation as calculated by TVM for each grid is presented by 15 classes. Of these classes only four are found in Costa Rica, Broadleaved warm mixed forest (A), tropical dry savanna (B), tropical seasonal forest (C) and tropical rain forest (D) (Fig. 2.4). Of the 18 Costa Rica grids seven had temperature/ precipitation values near threshold values causing changes in vegetation classes during the Monte Carlo simulations. These grids are found in the transition zone between the dry west part of Costa Rica and its humid east coast. The most humid and arid results are also given in Fig. 2.4. The observed threshold effects in the TVM for potential vegetation types seem less dominant than for the potential water-limited yield calculations. This may be due to the more refined and balanced classification boundaries use in TVM which are based on the BIOME model of Prentice et al. (1992).

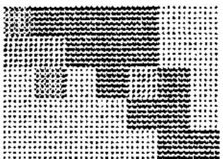
2.6 Discussion and Conclusions

Although only a small country was evaluated, Monte Carlo simulations demonstrated that the model sensitivity of the TVM in respect to water-limited crop yield-potentials was mostly determined by model parameters rather than by input variability of climate data. The dominating model parameters are criteria related to crop requirements and clustering of crop types into economic crop groups. When climate inputs are not near the specified crop requirements (Tab.2.1) a rather limited CV can be observed for the calculated outputs compared to the CV of the input data, illustrating the robustness of the TVM in respect to its climate data. When model thresholds are met or crossed a strong increase in the CV and the inter/intra grid variance coefficient can be observed. This suggests that the current model parameters and crop growth criteria are applied too rigorously in the TVM.

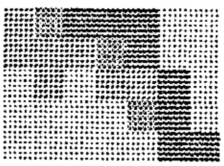
Potential Vegetation



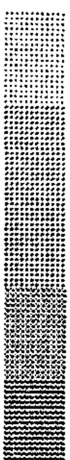
Mean (most common) output



Maximum 'Wet' output



Maximum 'Dry' output



= No vegetation

= Br,leav./warm mixed forest

= Tropical dry savanna

= Tropical seasonal forest

= Tropical rain forest

Fig. 2.4 **Potential Vegetation (see legend), the mean output with the wettest and driest outputs.**

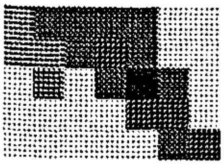
Apparently the crop requirements used are too coarse. It is therefore proposed to remove as many model criteria as possible. Another possible solution might be found in applying more gradual threshold values, using overlapping domains. The grouping of crops into economic crop-groups is not realistic. For example sugar cane and sugar beet have only in common that they are used to produce sugar. It is therefore proposed to group the crops in phenological/physiological groups with gradual transition criteria from one crop to the other instead of the current economic groups.

Only when the model parameters have been made less dominant in the model performance of the TVM of IMAGE 2.0, it will become relevant to collect more detailed and realistic climate data as currently available in IMAGE 2.0.

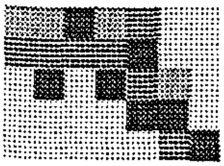
Our first model analysis for the terrestrial vegetation model of IMAGE 2.0 demonstrates that the limitations to successful modelling are more caused by lack of scientific insight rather than data availability and quality. The refinement of the TVM of IMAGE 2.0 should be sought in model improvement instead of data quality improvement.

The overall performance of the TVM for Costa Rica seems rather satisfactory (Tab. 2.2 and 2.4). The different climate environments yielded significantly different water limited yields. The calculated TVM results are applied on world region scale in the Land Cover Model (LCM) to allocate crops to agricultural grids (Zuidema et al., 1994). The crop distribution in IMAGE 2.0 is assumed to be directly related to the calculated crop production potential. In order to check the validity of this assumption for Costa Rica the calculated yield potentials for each grid cell is compared with crop distributions of maize, rice and beans in 1973 and 1984 (DGEC, 1976, 1987). It has to be noted that in reality crop distributions are influenced by many other factors unrelated to biophysical potential. In Fig. 2.5 the high potential yields and the grid cells were most beans, maize and rice were grown in 1973 and 1984 are given in dark grey colors. The maps demonstrate that the crop distribution in Costa Rica tends to change somewhat in time, but in general a superficial match between the calculated yield potentials and their general distributions can be observed, suggesting that the basic biophysical assumption in the LCM of IMAGE 2.0 has limited practical merit.

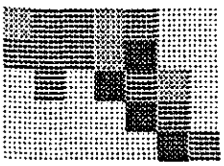
MAIZE:



Potential yields Maize. The grid cells with highest yields are black.

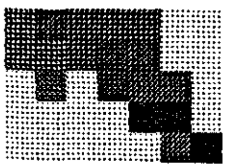


Distribution Maize areas in Costa Rica 1973. Grid Cells with most maize areas are darkest.

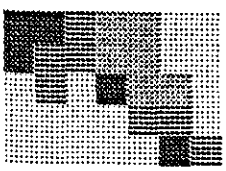


Distribution Maize areas in Costa Rica 1984. Grid Cells with most maize areas are darkest.

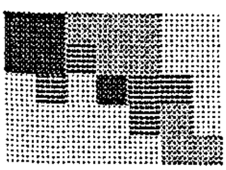
RICE:



Potential yields Rice. The grid cells with highest yields are black.

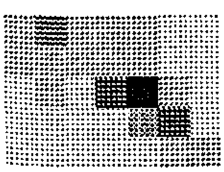


Distribution Rice areas in Costa Rica 1973. Grid Cells with most rice areas are darkest.

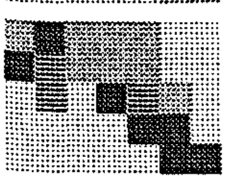


Distribution Rice areas in Costa Rica 1984. Grid Cells with most rice areas are darkest.

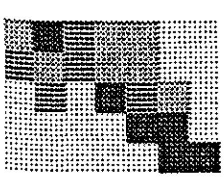
BEANS:



Potential yields Pulses. The grid cells with highest yields are black.



Distribution Bean areas in Costa Rica 1973. Grid Cells with most Bean areas are darkest.



Distribution Bean areas in Costa Rica 1984. Grid Cells with most Bean areas are darkest.

Fig. 2.5 **Comparison Potential yields of Maize, Rice and Pulses and their distributions in 1973 and 1984 in Costa Rica.**

CHAPTER 3:

Reconstructing land use drivers and their spatial scale dependence for Costa Rica (1973 and 1984).

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3.1 Introduction

Recent research indicates that human-induced conversions and modifications of land cover have significance for the functioning of the earth system (Bouwman, 1990; AMBIO, 1992; Turner et al., 1993, 1994). Most land cover modification and conversion is now driven by human use, rather than natural change (Houghton et al., 1991). In general, land use is viewed to be constrained by biophysical factors such as soil, climate, relief and vegetation. On the other hand, human activities that make use of or change land attributes are considered as the proximate sources of land use/cover change. Interpretations of how such land use/cover driving forces act and interact is still controversial, especially with respect to the assessment of the relative importance of the different forces and factors underlying land use decisions in specific cases (Turner et al., 1994). Relatively few regional comparative studies have explicitly addressed the role of these proposed driving forces, either separately or in combination. Still fewer have investigated statistical relationships between them (Turner et al., 1993).

An illustrative case study of investigating land cover changes (Skole and Tucker, 1993) demonstrated that land use changes that drive land cover change are tied to numerous human factors, some of which may be spatially distant from the area affected, leading to the conclusion that the processes involved in land cover and land use change operate across many spatial and temporal scales. An understanding of land use/cover change would thus be factually incomplete and lead to inadequate projections if its causes were sought only in the proximate sources of change or in forces operating within the area and the time-frame i.e. the scale, studied. The observation that causal links identified at one scale may not appear at other scales and v.v. is called the scale effect. Therefore, any attempt to reconstruct or link human and biophysical drivers of land use/cover can only be successful when this covers several different scales.

We investigate to what extent and how the distribution of Costa Rican land use/cover and its changes between 1973 and 1984 are related to biophysical and human factors at different spatial scales. Costa Rica was chosen as case study because this country is well known for it great biophysical diversity (Holdridge, 1967; Gómez, 1986), has a rapid expanding population and well documented census data. Moreover, Costa Rica is characterized by rapid changes in its land use/cover, especially deforestation (Keogh, 1984; Sader and Joyce, 1988; Harrison, 1991; Veldkamp et al., 1992).

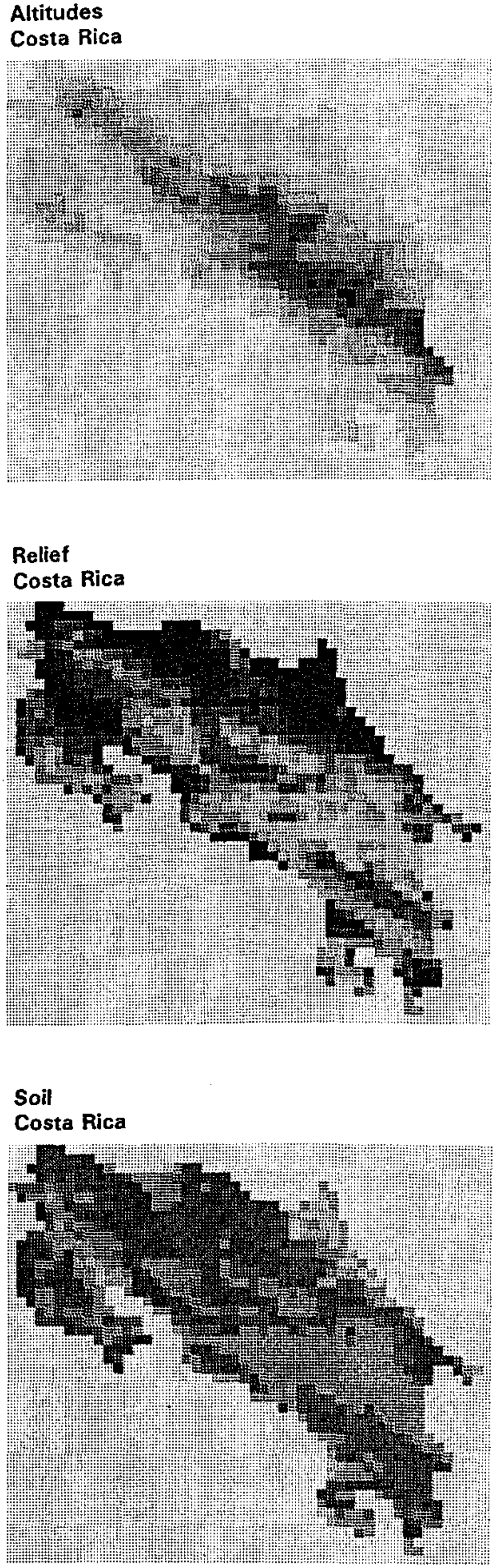


Fig. 3.1 **Biophysical environment of Costa Rica in 0.1° grids. Altitude (Highest grids are black), Relief (Flat is black and steep is almost white), Soil drainage (black is well drained and white in poorly drained).**

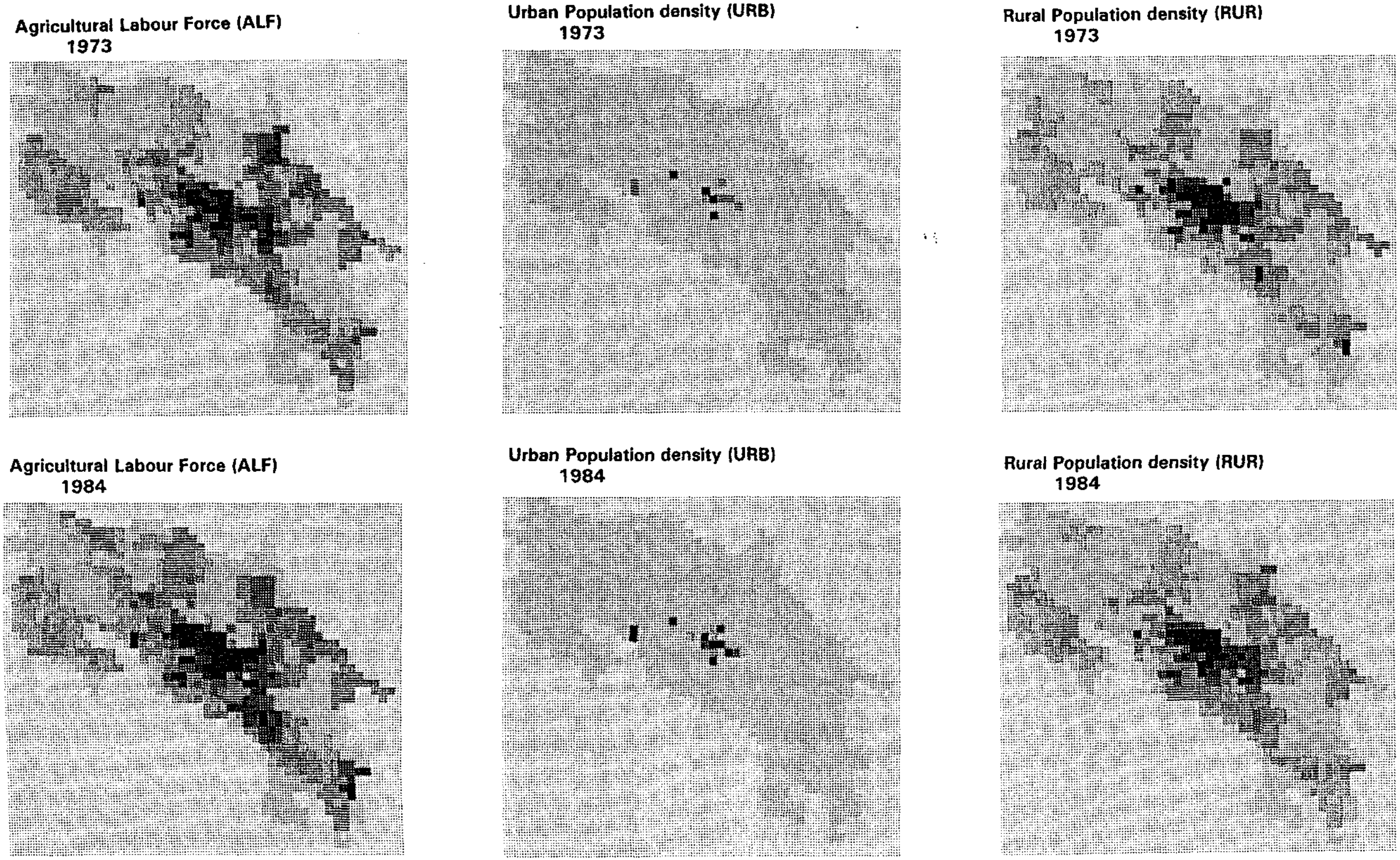


Fig. 3.2 **Population densities and distribution of Agricultural Labour Force, Rural population and Urban population in Costa Rica 1973 and 1984.** ***Black grids mark are the most densely populated areas,*** **derived from census data.**

3.2 Spatial and temporal scales

In every case study of land use/cover changes, units and processes have scale-related properties with dimensions defined in space and time. As in the case of other living systems, scale dimensions do not evolve necessarily in a gradual manner, but may display clear threshold effects. The step from, say, a grassy vegetation on a given pasture field to vegetation in a savanna landscape is not just cumulative, which means that the landscape and the way it is managed cannot be understood entirely by taking the sum of all individual pasture fields and the management actions on these fields. Although they are sometimes hard to visualize, other processes and units must be distinguished at higher levels. The scale at which the analysis is conducted will affect the type of explanation given to the phenomena. At coarse (aggregated) scales, the high level of aggregation of data may obscure the variability of units and processes, and may therefore produce meaningless averages. Predictions based at coarse-scale data and models are therefore considered inaccurate for regional and local assessments, because at the aggregate level local key processes may be obscured. On the other hand, it would be both impractical and inadequate to obtain detailed scale models for every local situation if there is no possibility of generalizing these models. We are thus confronted with two different scale properties that need to be taken into account: 1) each scale has its own specific units and variables; 2) the interrelationships between sets of variables and units can change with scale.
How can we then develop valid models at regional scales and deal with these two types of scale problems? The solution lies in the development of a truly hierarchical approach in both the observation and explanation of land use/cover change processes (Kolasa and Rollo, 1991). Once scale effects are known and quantified, models can be made for each measured scale level. The scale hierarchy may then function as a key to scale up and down relationships in space and time.

Nested scale analysis

A first step to unravel scale effects is to make certain that the collected data can be aggregated at, at least three different spatial scales (this is the minimal level principle of Odum, 1983). A way to do this, is to organize both the biophysical and socio/economic data in their respective hierarchies as proposed in a conceptual land use classification system of Stomph et al. (1994). Subsequently, these hierarchies must be compared and linked (matched) spatially. Socio-economic units only rarely coincide with biophysical units, and therefore processes and drivers do not overlap in space (the exception may be small islands as ecological and social communities). To avoid this discrepancy, matching may require the 'construction' of artificial scales based on grid aggregations. A major disadvantage of this grid approach is that one may loose information, because the minimum grid size becomes the most detailed level of analysis possible. Another disadvantage is the artificial nature of the units of analysis. However, once data are converted into grid units, similar and equal sized units without any spatial aggregation problem can be compared. An other advantage is that artificially gridded data can be aggregated into many different scales while data grouped in administrative boundaries, for example, can only be aggregated into a few predetermined scales. Costa Rica allows only aggregation from districts (n=419) into cantons (n=80), provinces (n=7) and Costa Rica (n=1). However, for statistical analysis a sufficient number of cases is available only at two levels (district and canton), too few for a nested scale analysis. We propose therefore to use artificial grid based spatial data sets to test the central hypothesis that relationships between driving forces will change with scale.

Nested aggregation may also apply to temporal scales. But such an analysis would require data covering considerable time spans, possibly up to 10^5 years to capture ecological evolutionary processes (see also Fresco and Kroonenberg 1992).

3.3 Materials and methods

Data

The basic data used in this study were obtained from the population and agronomic census of Costa Rica (DGEC, 1976a, 1976b, 1987a, 1987b) and from the preliminary atlas of Costa Rica (Nuhn, 1978). The census data on agriculture and population of 1973 and 1984 were available at district level (n=419). Previous research demonstrated that altitude (m), relief (classes from 0 (mountainous) to 10 (flat)) and soils (classes from 0 (poorly drained) to 10 (well drained)) (Fig. 3.1) give a good representation of the biophysical conditions including climate variability (Herrera, 1985, Brenes and Saborio Trejos, 1994). Population data consist of rural population, urban population and agricultural labour force. As the maps of Figure 3.2 demonstrate, the Costa Rican population is mainly concentrated in the Central Valley near the capital San José. The main land use/cover classes (Dominant cover) of Costa Rica (Fig. 3.3), have a specific distribution within the country which changed from 1973 to 1984 (Fig. 3.4) (in % land cover).

The census data were converted into grid cells. The selected minimum grid size (0.1° *geographical* grid, approx $7.5 * 7.5 = 56.25 km^2$ at the equator) was based on the estimated average district size, the most detailed spatial scale for the census data. The census data were matched with biophysical map data (Nuhn, 1978) which were converted into similar grids.

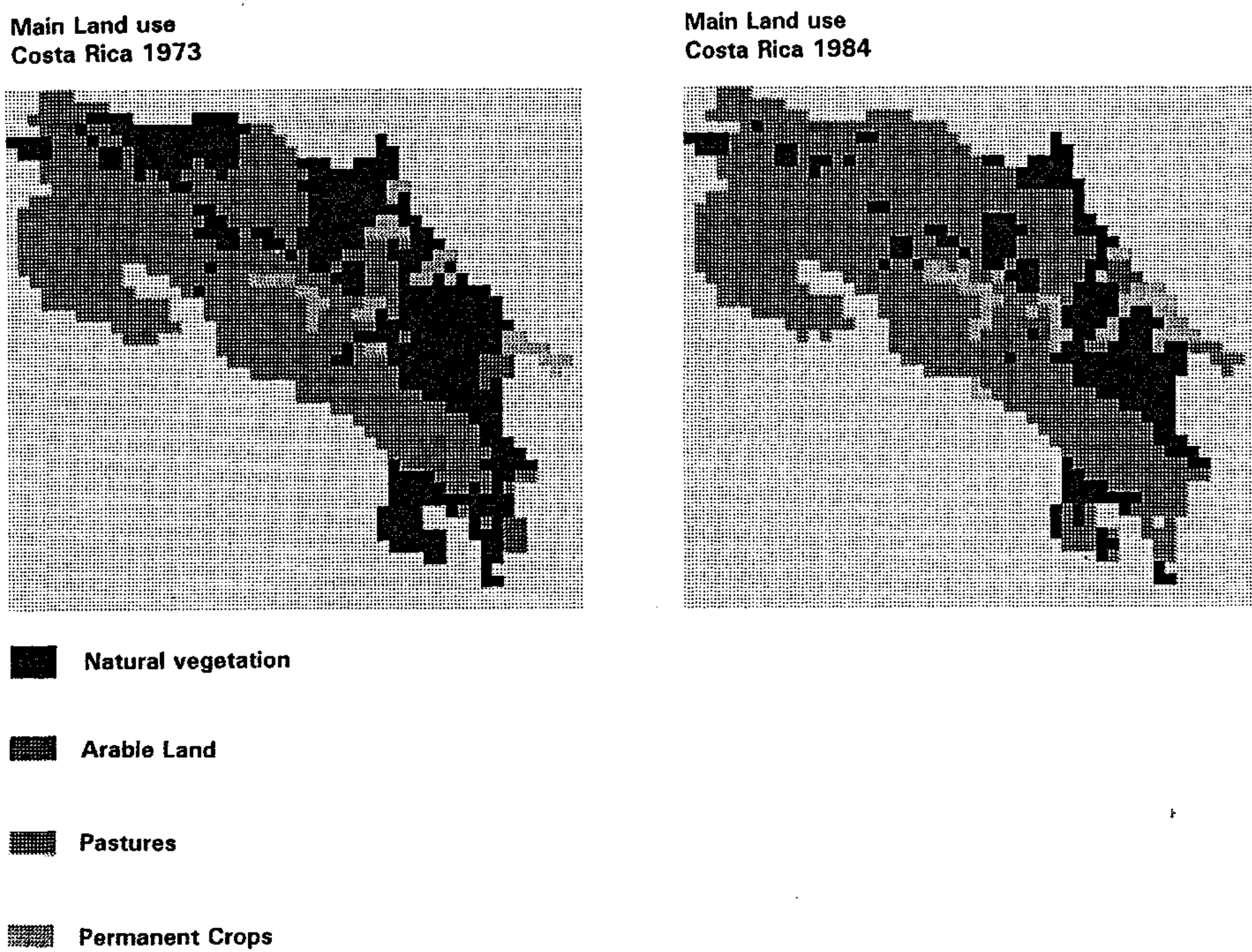
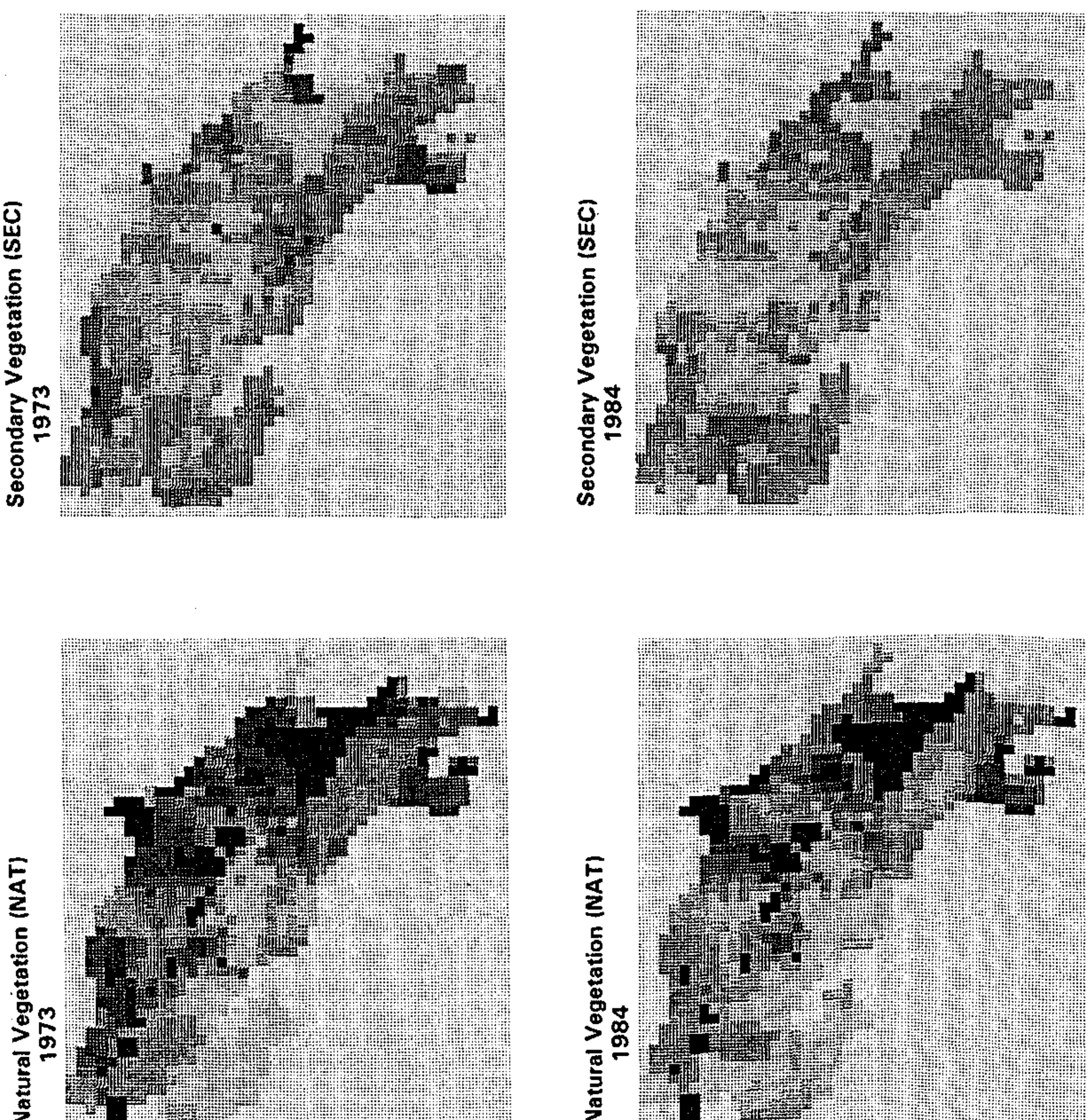
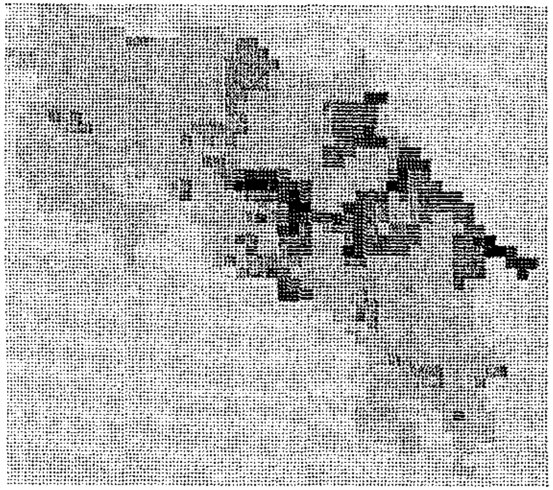


Fig. 3.3 **Main land uses in Costa Rica in 1973 and 1984, derived from census data. (see legend).**

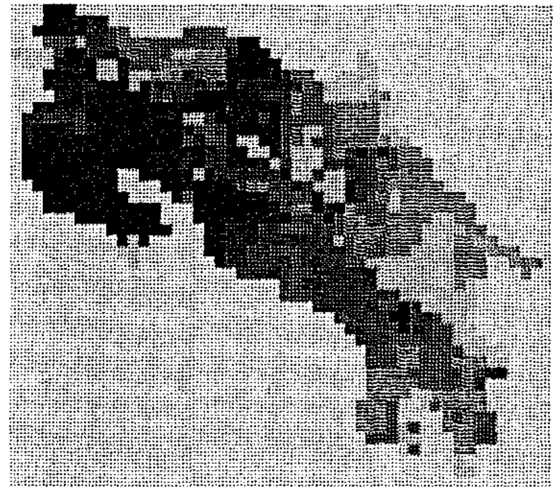
Fig. 3.4 **Land use/cover distributions of Permanent crops (white=0% black=70%), Pastures (white=0% black=70%), Arable land (white=0% black=35%), Natural vegetation (white=0% black=70%) and Secondary vegetation (white=0% black=35%) in 1973 and 1984. Derived from Census data.**



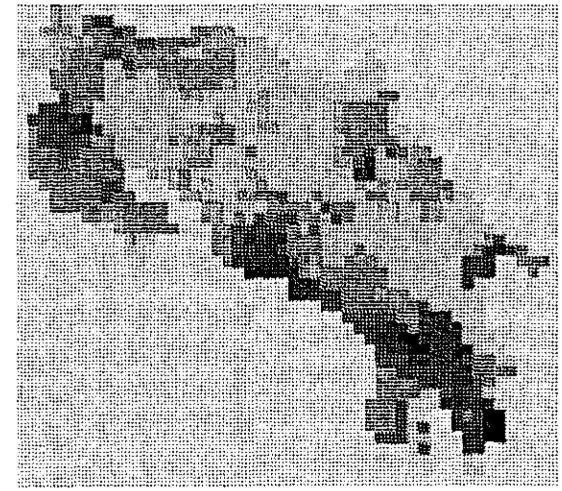
Permanent crops (PER)
1973



Pastures (PAS)
1973

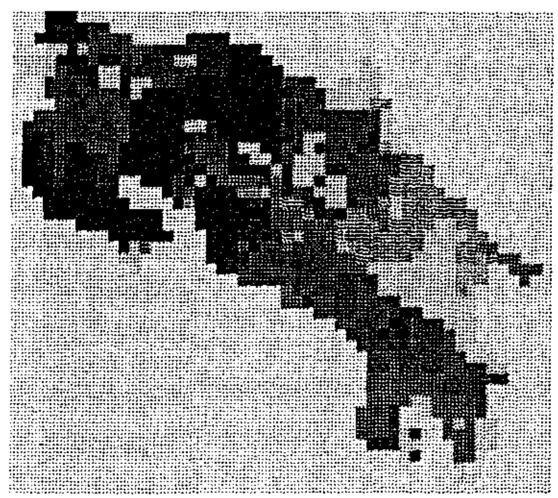


Arable Land (ARA)
1973

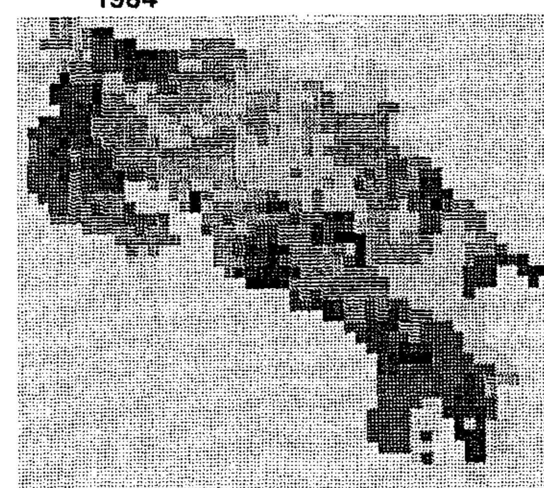


Permanent crops (PER)
1984

Pastures (PAS)
1984



Arable Land (ARA)
1984



In order to allow a systematic analysis of spatial scale effects, the 0.1° grid data were aggregated into larger grids. These larger grids are aggregations of 4 (225 km^2), 9 (506 km^2), 16 (900 km^2), 25 (1406 km^2), 36 (2025 km^2) 0.1° grid units, making five additional aggregated spatial scales. The new aggregated grid values were weighted averages of the included 0.1° grids, under the condition that at least 50% of the aggregated grids contributes a valid value. Values are valid when they are contributed by a grid with no missing value. This aggregating procedure was followed for all selected 1973 and 1984 data. The geographical specific data were managed and processed with IDRISI.

Statistical methods

The scale dependent relationships of the studied land use/cover systems with their possible human and biophysical land use drivers were investigated by multiple regression models (significance criterium = 0.05). To allow comparison of the regression modelling results for the different scales, standardized betas were calculated and used as a measure of the variable contributions. To end up with comparable models, the following multiple regression modelling strategy was followed. At the most detailed 0.1° grid scale level a stepwise regression procedure was carried out. This best fit model was then used at the higher aggregated scales using an enter regression procedure. This methodology has as major disadvantage that one excludes 'new' variables at the analysis of aggregated scales, which may lead to an incomplete system description. On the other hand will the model fit (coefficient of determination) give a quantitative measure of incompleteness of our system description. The advantage of this methodology is that one can accurately follow the changes in model fits and relative variable contributions with scale. This yields an insight in the scale-related trends of system behavior. Before the scale-related explanation of land use/cover variance was made, the interrelationships of the land cover and their potential drivers were studied by factor analysis, with principal component extraction and varimax rotation. All described statistical analysis was done with SPSSpc and SAS.

3.4 Results

FACTOR ANALYSIS OF THE COSTA RICAN LAND USE/COVER SYSTEM AND ITS POTENTIAL DRIVERS.

Factor analysis of the 1973 and 1984 data resulted in rather consistent factors explaining most variance (Tab. 3.1). The total variance in the *1973* data set can be described by 4 significant factors for all scales, explaining between 68 and 81% of the total variance. The factors can be interpreted as a population/permanent crop factor (factor 1), an arable land/secondary vegetation versus natural vegetation factor (factor 2 or 3), an independent biophysical factor (fact 2, 3 or 4) and a pasture versus natural vegetation factor (factor 2, 3 or 4). The relative importance of these factors seems to change with scale, as do the exact contributions of the various variables. The changing contribution of the variable urban

Tab. 3.1 A factor analysis, principal component extraction with varimax rotation, was made for the following data: Altitude, Relief, Soil drainage (SOIL), Rural population (RUR), Urban Population (URB), Agrarian Labour force (ALF), Permanent Crops (PER), Pasture (PAS), Arable Land (ARA), Natural Vegetation (NAT), Secondary Vegetation/Fallow (SEC). Only variables with a factor loading > 0.5 are listed.

1973

scales:	1	2	3	4	5	6
No. Grids:	1	4	9	16	25	36
Explained variance: (% of total)						
Factor 1:	28.2	27.9	30.5	31.6	37.3	36.1
Factor 2:	22.5	19.7	23.5	24.7	20.8	18.6
Factor 3:	11.6	10.7	12.0	11.6	13.7	14.7
Factor 4:	11.2	9.9	9.8	9.5	9.2	10.3
Total :	73.5	68.2	75.8	77.4	81.0	79.8
Factor composition:						
Fact 1:	PER RUR URB ALF	PER RUR ALF	PER RUR URB ALF	PER RUR ALF	PER ARA RUR ALF	PER RUR ALF
Fact 2:	ARA -NAT SEC	ARA SEC	SOIL PAS -NAT	RELIEF SOIL -ALTITUDE	ARA -NAT SEC URB	SOIL ARA -NAT SEC
Fact 3:	SOIL PAS -NAT	RELIEF -ALTITUDE	ARA -NAT SEC	ARA SEC	-RELIEF ALTITUDE	RELIEF -ALTITUDE
Fact 4:	RELIEF -ALTITUDE	PAS -NAT	RELIEF -ALTITUDE	PAS -NAT URB	SOIL PAS -NAT	PAS -NAT URB

1984

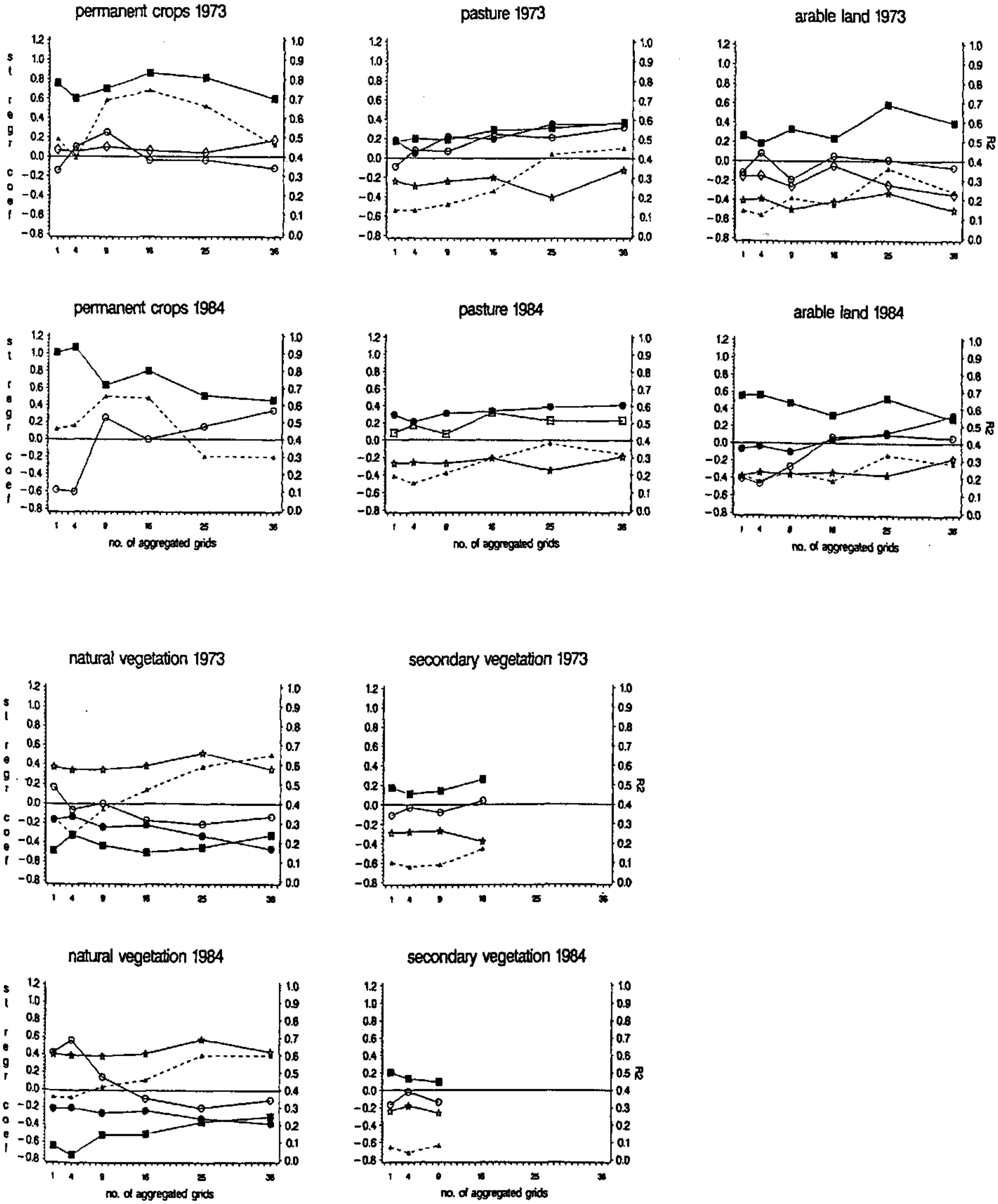
scales:	1	2	3	4	5	6
No. Grids:	1	4	9	16	25	36
Explained variance: (% of total)						
Factor 1:	28.0	27.8	30.1	32.6	34.2	35.9
Factor 2:	22.7	21.9	26.1	23.8	19.7	17.2
Factor 3:	12.0	12.2	11.7	10.5	13.4	13.9
Factor 4:	10.6	11.2	10.2	9.5	9.7	11.3
Total :	73.2	73.1	78.2	77.4	77.0	78.3
Factor composition:						
Fact 1:	PER RUR URB ALF	PER RUR URB ALF	PER RUR URB ALF	PER RUR ALF	PER RUR ALF	SOIL PAS -NAT
Fact 2:	ARA -NAT SEC	ARA -NAT SEC	ARA -NAT SEC	RELIEF SOIL -ALTITUDE	ARA -NAT SEC	RUR ALF
Fact 3:	SOIL PAS -NAT	SOIL PAS -NAT	SOIL PAS -NAT	ARA -NAT SEC	SOIL PAS -NAT	RELIEF -ALTITUDE URB
Fact 4:	RELIEF -ALTITUDE	RELIEF -ALTITUDE	RELIEF -ALTITUDE	PAS URB	-RELIEF ALTITUDE URB	PER ARA SEC

population is particularly interesting. At detailed spatial scales the population factor has no significant contribution at all, while at the more aggregated scales (scale 4, 5 and 6) it is related to the pastures versus natural vegetation or arable land versus natural vegetation.
The variance within the *1984* data set can also be described by 4 significant factors, explaining between 73 and 78% of the total variance. The factors can be interpreted as a population/permanent crop factor (factor 1 or 2), an arable land/secondary vegetation versus natural vegetation factor (factor 2 or 3), an independent biophysical factor of altitude and relief (fact 2, 3 or 4) and a pasture/soil drainage versus natural vegetation factor (factor 1 or 3). The relative importance of these factors also changes with scale, as do the exact contributions of the various variables. Again the variable urban population changes with scale.

SPATIAL SCALE DEPENDENCE OF LAND USE/COVER AND ITS DRIVERS

The factor analysis demonstrates that factor contributions and compositions change with scale, confirming a spatial scale dependence. To elaborate these scale effects, Costa Rican land use/cover was modelled statistically with multiple regression on the six different spatial scales for the two available years, 1973 and 1984. Multiple regression models were made for all five land use/cover classes, using only biophysical and human explanatory variables. The results are condensed into figures displaying model fits (R^2=dotted line and right axis) and standardized betas (left axis) for all six scales given as number of aggregated 0.1° grids (Figs. 3.5 to 3.8). Only the models significant at the 0.05 level are plotted. Due to the limited number of cases at the higher aggregated scales the multiple regression models are not always significant.

Fig. 3.5 **Scale dependent (scale in no aggregated 0.1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for Permanent crops, Pastures, Arable land, Natural vegetation and Secondary vegetation in 1973 and 1984.**



---▲--- = Coefficient of determination

Regression coefficients:

● = soil drainage (SOIL)
■ = agr. labour force (ALF)
☆ = altitute (ALT)
⌑ = rural population (RUR)
○ = urban population (URB)
◇ = relief (REL)

Natural Vegetation

Natural vegetation in 1973 and 1984 (Fig. 3.4) is reasonably well modelled with multiple regression (R^2 ranges from 25-65%) with the variables altitude, soil drainage, urban population and agricultural labour force, displaying a general and gradual increase of model fit with higher aggregated scales for both years (Fig. 3.5). The model fit optimum for both years seems to be situated outside the scale window explored here. The relative contributions of the explaining variables, as shown by their standardized regression coefficients (Fig. 3.5) are especially interesting for the variables agricultural labour force and urban population, which display a relatively decreasing contribution at more aggregated scales, while the negative contribution of the soil drainage increases slightly with aggregation level. The positive contribution of altitude hardly changes with scale. Apparently, a systematic spatial scale dependence exists for the multiple regression models for natural vegetation in 1973 and 1984. *Interpretation:* Most natural vegetation in 1973 and 1984 is found at higher altitudes and on poorly drained soils, an effect which can be ascribed to the deforestation strategies followed in Costa Rica (Sader and Joyce, 1988; Veldkamp et al., 1992). The negative contribution of the agricultural labour force and, for the more aggregated scale levels, urban population, may be explained by the fact that few people live in areas with natural vegetation (mostly tropical rain forest), partly due to limited access and to regulations (reserves). The fact that many forest reserves and national parks are found on the mountains surrounding the densely populated and urbanized Central Valley may (Fig. 3.2 and 3.3) may account for the strong positive contribution of urban population in explaining the natural vegetation variance at more detailed scales.

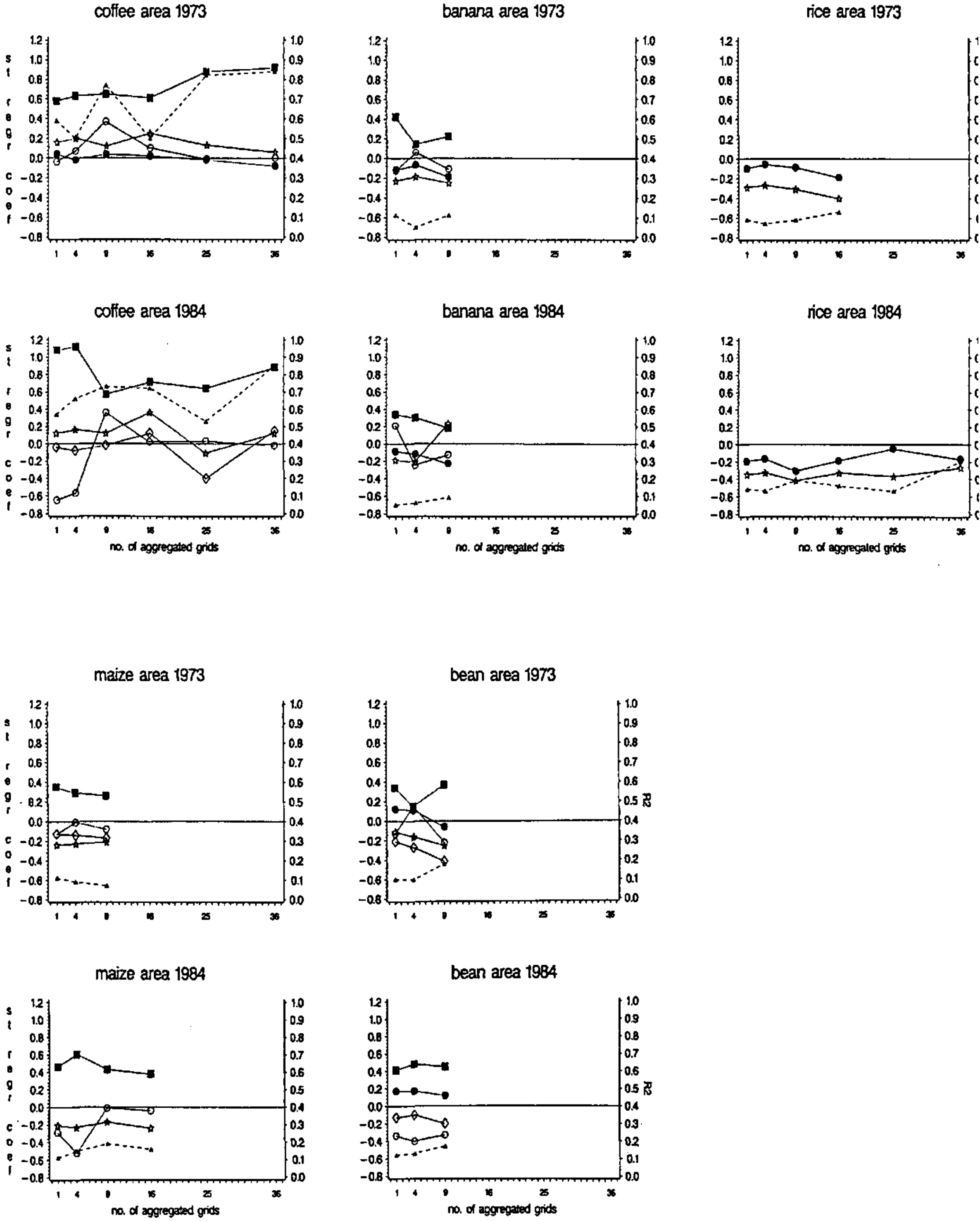
Secondary Vegetation

This poorly defined land use/cover class (Fig. 3.4) acts as a residual group between natural vegetation and grassland/arable land. This dependent status is confirmed by the factor analysis. Secondary vegetation is only modelled significantly for the more detailed scales by the independent contributions of altitude, urban population and agricultural labour force for both years. Model fits are generally poor, and range from 5 to almost 20% of the total secondary vegetation variance (Fig. 3.5). The explaining variable altitude and to a lesser extent urban population have negative relationships with secondary vegetation, while the remaining variable agricultural labour force displays a positive relation. The contributions change only slightly with scale, while model fits remain poor. *Interpretation:* In both 1973 and 1984 most secondary vegetation is found at lower altitudes in rural ares where a considerable agricultural labour force is active. The poor model fit may be explained by the fact that the decisions to abandon arable lands and/or pastures or to partially remove the natural vegetation (shifting cultivation and other rotation practices) are dominant at more detailed spatial scales than currently explored in this study (Reiners et al., 1994).

Pastures

Pasture (Fig. 3.4) variability is modelled significantly for both years by a model with altitude, soil drainage, urban population and agricultural labour force as explaining variables. Model fits (Fig. 3.5) range between 10% and 45% of total variance, and display model fit maxima at scales of 25 and 36 aggregated 0.1° grid units. The relationships of the explaining variables change somewhat with scale. Soil drainage has a positive contribution which slightly increases with aggregated scales while the negative relationship of altitude with pastures somewhat decreases at higher aggregated scales. For 1973 the contributions of both urban population and agricultural labour force are positive and increase with aggregated scales. The 1984 pastures demonstrate a positive contribution of rural population which increases somewhat with spatial scale. *Interpretation:* Pastures are predominantly found at lower altitudes on well drained soils in areas where a considerable agronomic labour force or rural population exists. At more detailed spatial scales more pastures are found away from urban centers.

Fig. 3.6 **Scale dependent (scale in no aggregated 0.1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for the permanent crops: Coffee and Banana areas and for Annual crops: Rice, Maize and Bean areas in 1973 and 1984.**



---▲--- = Coefficient of determination

Regression coefficients:

● = soil drainage (SOIL) ⌑ = rural population (RUR)

■ = agr. labour force (ALF) ○ = urban population (URB)

☆ = altitute (ALT) ◇ = relief (REL)

Permanent Crops

The variance in Permanent Crop distribution (Fig. 3.4) was modelled with relief, urban population and agricultural labour force as independent explaining variables displaying changing fits (30% to 75%) (Fig. 3.5). Maximum fits are found at 9 and 16 aggregated 0.1° grids scales. In 1973 the relative contributions of the explaining variables change only gradually. The agricultural labour force continues to have a strong positive relationship with permanent crops while urban population has alternating negative and positive relationships, and relief displays only a slight positive relationship with permanent crops. The 1984 data show a clearer change in the relative contributions of the explaining variables (Fig. 3.5). The positive contribution of agricultural labour force decreases at a less detailed (more aggregated) spatial scale while the urban population permanent crops relation switches from strongly negative to a positive relation at higher aggregated scales. The 1984 permanent crop model demonstrates a change in both model fit and variable contribution with scale. *Interpretation:* As a group permanent crops are mainly found in relatively flat areas (positive relief contribution) and in areas with a substantial agricultural labour force. The changing contributions of urban population may be explained by a spatial scale effect. Permanent crops are not found too near to urban centers (negative relationship at detailed scales), but preferably at a convenient transportable distance from the urban population (positive contribution optimum at aggregation level of 9 0.1° grids). The deviations at the higher aggregation scales for 1973 and 1984 are not directly clear, but may point to a change in distribution of permanent crop areas.

To gain more insight into the aggregated group of permanent crops the distribution of its two most important crops, Coffee and Bananas, was studied.

COFFEE AREAS are well modelled by altitude, relief (only 1984), soil drainage (only 1973), urban population and agricultural labour force (Fig. 3.6). Model fits range from 50 to 85%. Agricultural labour force and altitude have positive contributions while the contributions of urban population, soil drainage and relief are scale dependent. *Interpretation:* Coffee areas are found at higher altitudes and in areas with a relatively large agricultural labour force. Like most permanent crops they are related to urban centers but are mainly found at some distance from the cities. The relationship with soil drainage (1973) and relief (1984) depends on the spatial scale of interest. Coffee areas are apparently associated with both steep and flat areas with both poor and well drained soils. The relief contribution in 1984 confirms that coffee has expanded to the steeper slopes on the fringe of the Central Valley.

BANANA AREAS, which are mainly limited to the Atlantic zone, are poorly modelled (model fits around 10%) with contributions of altitude, soils, urban population and agricultural labour force (Fig. 3.6). *Interpretation:* Banana areas are found at lower altitude in areas with poorly (1973) and well drained (1984) soils with a considerable agricultural labour force, as confirmed by Huising (1993).

Arable Land

For both years the arable land regression models (Fig. 3.4) have model fits between 10 and 40%. Arable land is modelled by altitude, relief (1973), soil drainage (1984), urban population and agricultural labour force and displays a model fit maximum at a scale of 25 aggregated 0.1° grid units (Fig. 3.5). Model fits change less gradually with scale than the previous land covers. The standardized regression coefficients (betas) of the explaining variables change rather irregularly with different scales, but their changes are comparable for both modelled years, suggesting a systematic (non random) source. A generally strong positive relationship between agricultural labour force and arable land is combined with a consistent negative relationship between arable land and altitude and relief. Less consistent relationships with changing positive and negative contributions can be observed for soil drainage and urban population.

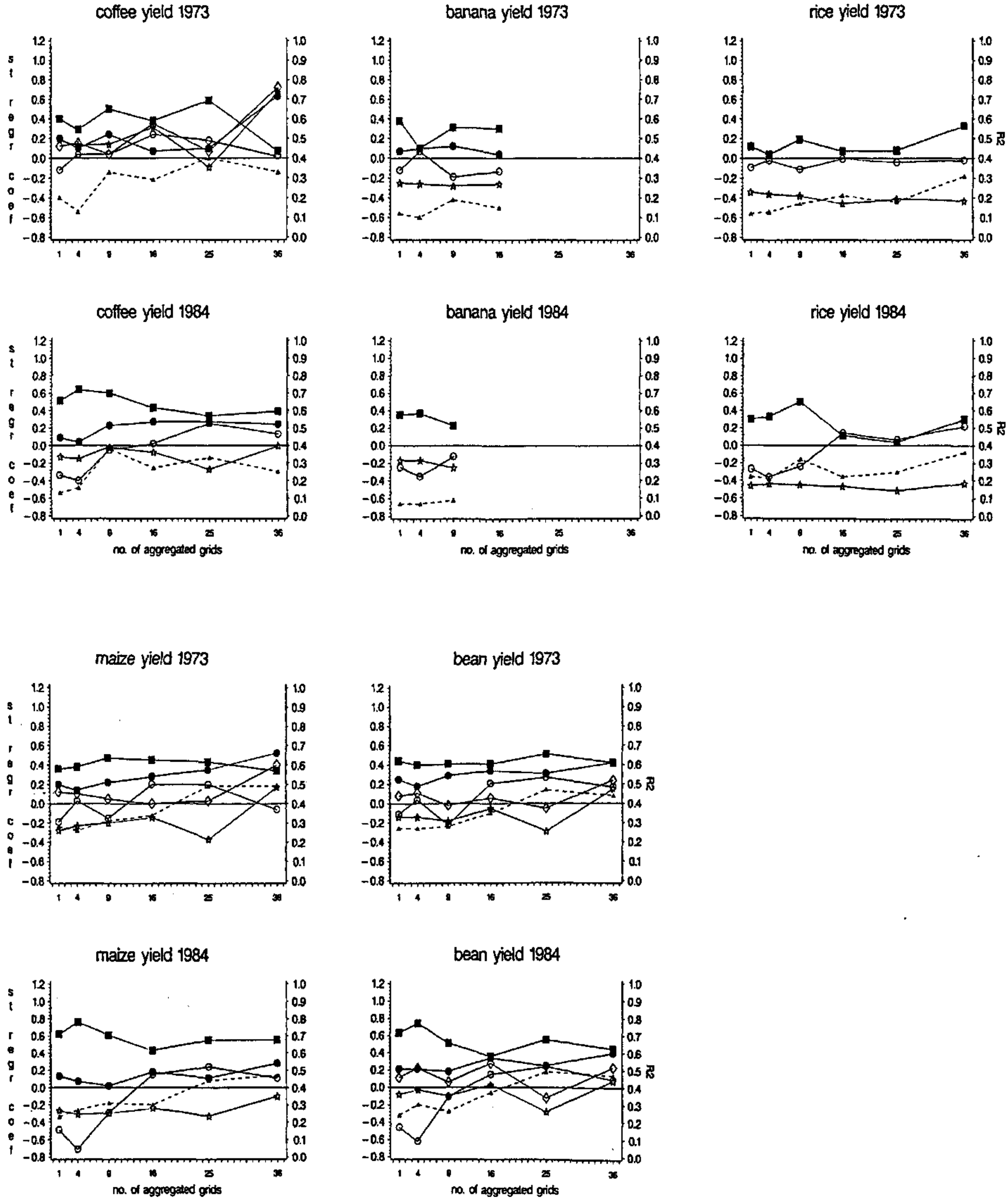
Interpretation: Arable lands in 1973 and 1984 are mainly situated at lower altitudes in relative flat areas (1973) where a considerable agricultural labour force is available, and obviously situated outside the urban zones. At more detailed spatial scales, in 1984, the arable land is not allocated on the best drained soils, but at more aggregated scales they are mostly associated with well drained regions. This spatial scale effect may be due to the differences in access to land and in production goals of various users of arable lands. Large commercial enterprises producing for export and the national market have more capital and can allocate their arable land in favorable conditions, while peasant household farms, producing for the regional and local markets, often have few alternative choices leading to sub-optimum production conditions (inputs) or to convert natural vegetation on imperfectly drained soils into arable land. Because arable land is also an aggregated group of different land uses and covers, the distribution of three annual crops (Maize, Rice and Beans) are studied in more detail (Fig. 3.6).

MAIZE AREA distribution is only poorly modelled by altitude, relief (1973), urban population and agricultural labour force (model fits range between 5 and 20%). Altitude and urban population have a negative contribution, while agricultural labour force contributes positively. *Interpretation:* Maize areas are apparently mainly found at lower altitudes with a considerable agricultural labour force outside urban regions.

RICE AREAS are more successfully modelled for 1984 (fit ranges from 15 to 30%) than for 1973 (fits between 2 and 13 %). In both cases only biophysical variables contributed significantly to the model. Altitude and soil drainage contributed negatively, while relief (1984) was positively related to rice areas. *Interpretation:* Rice areas are mainly found at lower altitudes on poorly drained soils. The fact that the distribution of rice areas is strongly biophysically related at all scales suggests that rice production is well technically optimized in the most suitable areas and probably mostly produced as a commercial crop.

BEAN AREAS are poorly modelled (model fits range between 5 and 20%) with a positive contribution of soil drainage and agricultural labour force, combined with a negative contribution of altitude (1973), relief and urban population. *Interpretation:* Bean areas are mainly found in areas with a considerable agricultural labour force and grown on well drained soils at lower altitudes (1973) and on sloping areas away from urban centers. The similarity with the maize area model is obvious. Because both crops have not such a clear biophysical optimization as rice, they are most probably grown both by large producers and by small holders.

Fig. 3.7 **Scale dependent (scale in no aggregated 0.1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for the yields of Coffee Rice, Maize and Bean yields in 1973 and 1984.**



---▲--- = Coefficient of determination

Regression coefficients:

● = soil drainage (SOIL) ⌑ = rural population (RUR)

■ = agr. labour force (ALF) ○ = urban population (URB)

☆ = altitute (ALT) ◇ = relief (REL)

Crop yields

Land cover is determined by land use, which also determines the yields obtained. To unravel land use incentives behind the land cover distribution, an analysis of crop yields (in kg/ha) in 1973 and 1984 (Fig. 3.7) was made for the permanent and annual crops whose distribution was already investigated, Coffee and Banana (as permanent crops) and Maize, Rice and Beans (as annual crops).

COFFEE YIELDS: are reasonably (model fits range from 15 to 40 %) modelled with positive contributions of agricultural labour force, soil drainage and relief, together with changing contributions of altitude and urban population. A large agricultural labour force and well drained soils on relatively flat areas seem to be related with high coffee yields. Furthermore, higher yields are obtained in areas not too close to urban centers. In 1973, higher yields were found at relatively higher altitudes while 1984 yields were higher at relative lower altitudes. This difference suggests a climatic cause but may also be related to land degradation between 1973 and 1984 in coffee fields at higher altitudes, which usually corresponds with steeper slopes.

BANANA YIELDS: are poorly modelled (fits between 10 and 20%) by positive contributions of soil drainage and agricultural labour force combined with negative contributions of altitude and urban population. The higher banana yields are obviously found at the lower altitudes on the well drained soils (1973) with a relative large agricultural labour force and a relatively small rural population, a condition valid for the Atlantic Zone where most bananas are grown (Fig. 3.4).

MAIZE YIELDS: are reasonably modelled (fits between 20 and 50%) with positive contributions of agricultural labour force, soil drainage and relief (1973) and negative contributions of altitude. The urban population contribution changes with spatial scale. This model demonstrates again that higher yields are found when a relatively large agricultural labour force is available at lower altitudes combined with flat well drained soils and not near urban centers.

RICE YIELDS: are fairly modelled (fits between 10 and 35%) with a positive contribution of the agricultural labour force and a negative one of altitude. The contributions of urban population are different for the two years. Higher rice yields are obtained at lower altitudes and with a large agricultural labour force. The changing relations of the urban population and rice yield may be explained by the fact that in 1973 rice areas were generally situated away from the cities but in 1984 a large irrigation scheme was developed near the town of Puntarenas, changing the spatial distribution, and a such accounting for the changing contribution of urban population in the rice yield regression models.

BEAN YIELDS: are reasonably modelled (fits range from 25 to 50%) with positive contributions of agricultural labour force, soil drainage, and relief combined with a general negative contribution of altitude and changing contributions of urban population. Again the combination of flat areas at lower altitudes, a large agricultural labour force and well drained soils seems to contribute to higher yields. The spatial relationship with urban population indicates that higher yields are obtained in rural areas.

Yield Interpretations: The general spatial effect of lower yields of Coffee, Rice, Maize and Beans near urban centers may be explained by sub-optimum production conditions. Because the average farmer in Costa Rica strives to a financial optimization of its household (Kruseman et al., 1994), a relative large amount of time may be spend working off-farm. With relatively good wages and low market prices, yields will tend to be lower (sub-optimum) due to limited labour availability and management at the smaller farms. The availability of jobs in urban centers could account for the relative lower yields on non-commercial farms near urban centers. This interpretation suggests that higher commodity prices and lower urban wages would lead to an intensification of the smallholder farming in peri-urban areas of Costa Rica. Similarly, the lower yields of the commercial crops Coffee and Rice near urban centers may be explained by the relatively smaller or more expensive agricultural labour force compared to the more rural areas. It is also possible to interpret the observed yield-urban population relationships in terms of biophysical degradation as suggested by Hall and Hall (1993). The older agricultural areas which are generally thought to be found near the urban centers are considered as the most degraded ones, accounting for the lower yields. Most probably such a degradation effect can not be excluded, but since severe land degradation is not only limited to peri-urban areas (Alfaro et al., 1994 and Pollak and Corbett, 1993), and because off-farm income may compensate loss of soil fertility through the purchase of fertilizers, we think that this biophysical effect is less important in explaining the yield regression models.

<u>Changes in Costa Rican land cover from 1973 to 1984 and their potential drivers</u>

Finally, the changes in land use/cover distribution from 1973 to 1984 were modelled with multiple regression for the six spatial scales (Fig. 3.8). The changes in land use/cover were modelled with changes in population and the specific biophysical conditions. In general, model fits were poor and scale-specific, this might be related to the non-linear characteristics of the modelled changes. Since we have only data of two different years we can only assume that the changes are linear. When data of more years become available transformations may contribute to better model fits. Changes in natural and secondary vegetation resulted in a hardly significant regression model with generally very poor fits (less than 10%). The changes in permanent crops have a model fit optimum at scale 4 (31%) with a strong positive contributions of rural population and a less important positive association with altitude. An increase in permanent crops seems thus related to an increase in rural population mainly at higher altitudes. This picture is confirmed by the multiple regression model on changes in coffee areas which has a good models fits (up to 93% at scale 6). Apart from the rural population the growth in urban population seems related to an increase of coffee areas near the urban centers but this increase took mainly place on less well drained soils in steeper areas. The model for changes in pasture areas has a best fit of 27% at scale 4 with only positive relations between pasture changes and relief, soil drainage and rural population growth, suggesting that an increase in pastures was related to an increase of the rural population and took place on well drained, relatively flat areas. The arable land change model has fits up to 36% at scale 3, with positive relations between arable land changes and both agricultural labour force changes and relief, combined with a negative contribution of soil drainage and urban population changes. A decrease in arable lands seems thus related to a decreasing agricultural labour force and an increasing urban population and is found in relatively steeper areas on well drained soils.

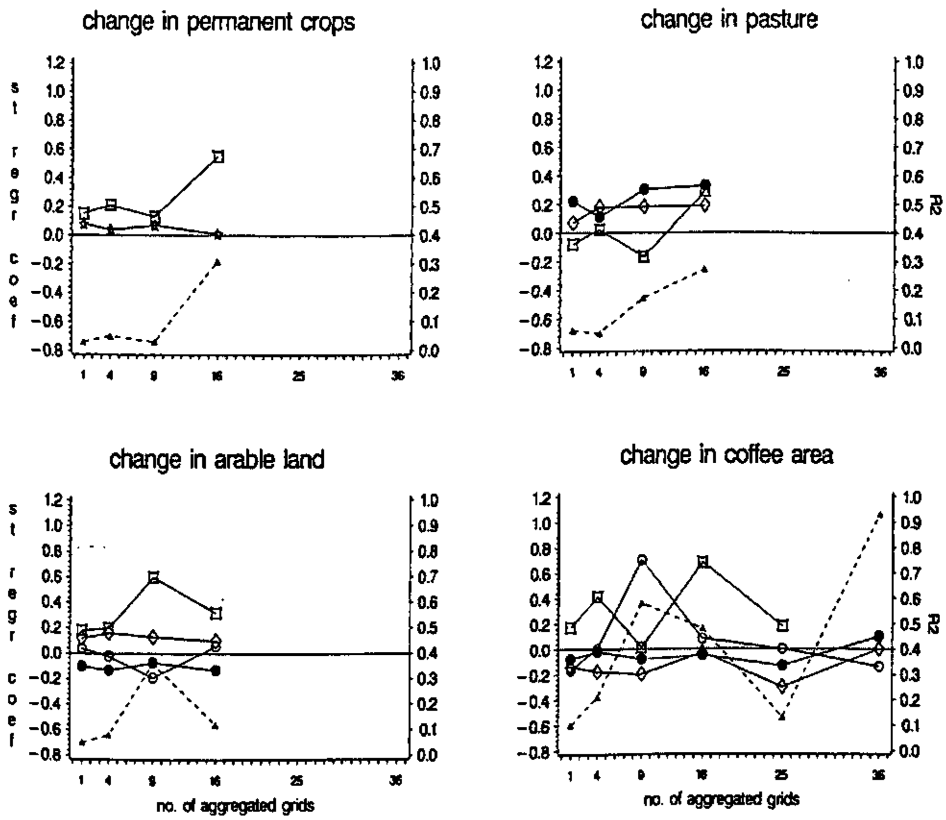


Fig. 3.8 **Scale dependent (scale in no aggregated 0.1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for the changes in Permanent Crops, Arable lands and Pastures and Coffee areas from 1973 to 1984.**

---▲--- = Coefficient of determination

Regression coefficients:

● = soil drainage (SOIL)	⌑ = rural population (RUR)
■ = agr. labour force (ALF)	o = urban population (URB)
☆ = altitute (ALT)	◇ = relief (REL)

3.5 Overall interpretation, discussion and Conclusions

The described changing model fits and varying variable contributions within the multiple regression models point clearly to a scale dependence of the Costa Rica land use/cover system. The fact that each land use/cover type has its own, and for both years consistent, specific scale relationships suggests that land use/cover drivers even if they vary in time have consistent impacts. This apparent stability allowed us to make a more in depth analysis/interpretation of Costa Rican land use/cover system dynamics from 1973 to 1984.

Costa Rican land use/cover system dynamics and its drivers

By its almost similar factor compositions for both years the factor analysis confirmed that the mechanisms and processes which steered the land use/cover system as such did not change very much during eleven years. Demographic factors (urban and rural population growth) are main drivers of land use *changes* as such, while the biophysical conditions merely act as constraints to where and what changes take place. The interrelationships of the different land use distributions as described by factor analysis indicates that certain land use/covers, like permanent crops, pastures and arable land distributions are unrelated to each other. *Permanent crops* are mainly grown for urban consumption and/or export and are therefore spatially related to the urban centers and their related infrastructure. Although much meat goes to the cities and is exported, *pasture* distribution is not very clearly driven by the urban population, (only a positive relation between urban population and pasture distribution in 1973), but mostly by the rural population converting natural vegetation (forest) into pastures. The observation that the cattle density (correlation coefficient between pasture area and number of cattle = 0.98 at cantonal level in 1973 and 1984, (DGEC, 1976a, 1987a)) in Costa Rica is not related to biophysical factors suggests a rather extensive pasture management. Although cattle density increased somewhat between 1973 and 1984, the cattle density is far from maximum and could be much more intensive and better biophysically optimized, a conclusion also reached by Ibrahim (1993) on different evidence. This is also confirmed by the observation that cattle is also a status symbol and provides security for small holders (Alfaro pers. com. september 1994). This indicates that deforestation for pasture expansion in Costa Rica from 1973 to at least 1984 was not driven by land shortage due to excessive cattle densities.

Arable lands in 1973 and 1984 can be grouped, based on markets and goals, into two categories, the large 'commercial enterprises', producing for urban centers and export and the regional and local market oriented 'farms' mainly producing food for the rural population. Commercial large scale rice, bean and maize producers, are directly related to the available labour force and usually are well managed and allocated to the best available biophysical conditions. The 'local farms' (beans and maize) are often owned by farmers with off farm activities often leaving insufficient time for optimizing their land management. The limited time for farm activities is probably the main reason that arable lands are associated with secondary vegetation (especially 1973) and deforestation (Tab.

3.1). The prevalence of shifting cultivation and fallow systems favors extensive areas with regrowth of secondary vegetation. Again deforestation is not linked to land shortage or high population densities. Low input management and unfavorable biophysical conditions made arable lands of local farms less productive than the relatively well managed and optimized commercial lands. This 'under use' of local arable lands was also reported in a regional study of the Atlantic Zone (Alfaro et al. 1994) where higher production potential are predicted when current land use practices would be better adapted to existing biophysical conditions.

Pasture and arable land proportions in 1973 and 1984 at various scales demonstrates that deforestation itself (logging, and land occupation) was probably one of the most profitable activities in rural areas with remaining natural vegetation. As Harrison (1991), Lutz and Daly (1991) already pointed out and our results strongly confirm, the lack of a well established forest policy combined with certain agricultural subsidies seem the main human cause for rapid deforestation. Even without a population growth or migration, deforestation would have taken place between 1973 and 1984.

Summarizing, we observe in Costa Rica two land use/cover trends during both 1973 and 1984, (a) intensification (mostly of permanent crops) in the Central Valley and its surroundings related to high population densities, where agriculture (mainly coffee) is extended to steeper and less favorable soils; and (b) land use expansion in remote areas with natural vegetation, where the agricultural lands increased at the cost of natural vegetation. Deforestation was mostly driven by the open access status of the forest and by governmental subsidiaries on certain crops (Lutz and Daly, 1991; Harrison, 1991; Kruseman et al., 1994). The shortage of arable land or pastures related to high population or cattle densities did not seem to play a significant direct role in driving Costa Rican deforestation from 1973 to 1984. Unfortunately, similar deforestation trends are still reported for the last decade (Hall and Hall, 1993) suggesting a need for more effective policies to stimulate intensification of cleared land. We agree that such intensification should be based on a biophysical optimization of land use (Reiners et al., 1994; Alfaro et al., 1994).

Nested Scale analysis

Our Costa Rican case study demonstrates that relationships between land use/cover and their biophysical and human drivers can be strongly spatial scale dependent. Furthermore, the nested scale analysis shows that great caution should be taken when interpreting such relationships. The differential results reported by different investigators on apparently similar subjects may well have scale related origins.

To evaluate the effect of using artificial grids/scales, a statistical analysis of the census data using the administrative units instead of the grids was made. This analysis showed scale-related (district and canton) relationships for the multiple regression models, that were very consistent with the results obtained from the statistical analysis of the grid data, indicating that the application of artificial units (grids) did not disturb the results too much.

The applied regression strategy, excluding 'new' variable at higher aggregation scales, seems to have had no major effect on the regression results since most models have increasing model fits (sometimes up to 90%) at more aggregated scales. It should be emphasized that this exclusion may in cases with poor model fits considerably hamper correct interpretations of scale related land use/cover dynamics.

There are, of course, some limitations to the described grid aggregation methodology. First, the reconstructed scale dynamics and relationships are only valid for the selected time span in the investigated area, and exclude processes and effects which operate on more detailed or more global scales. Since it is virtually impossible to address all these scales it is something we have to live with. Secondly, the scale analysis demands an enormous amount of data making it difficult to repeat such exercises on more detailed scales in a similar way. When the land use/cover displays a relatively stable scale hierarchy, the nested scale analysis can be applied to make a more in depth analysis and interpretation of system dynamics. Despite the poor time resolution (only data for two years), we were able to identify and quantify the most important land use land use drivers and constraints and their scale related effects in Costa Rica between 1973 and 1984. Our results and interpretations could be partly confirmed by results of other investigations using other data and methodologies.

In Costa Rica land use/cover has, like natural ecological systems (Rosswall et al., 1988; Kolasa and Pickett, 1991; Reed et al., 1993), its specific spatial dependencies. Land use/cover heterogeneity seems thus to be like ecosystem and landscape heterogeneity a multi-scale characteristic (Milne, 1991) and can therefore best be treated and described as a nested hierarchical system. This does not imply that every land use/cover system must necessarily be hierarchical, but it indicates that complex land use/cover systems may take on such a structure.

CHAPTER 4:

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

By: A. Veldkamp and L.O. Fresco

4.1 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 (≥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 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 permit 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.

4.2 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, p 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.

<u>Biophysical drivers:</u>

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 (Dalal and Mayer, 1986; Juo and Lal, 1977). 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).

<u>Human drivers:</u>

Of the human drives, 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 fibers 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.

4.3 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.

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.

4.4 Model Structure and Inputs

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.

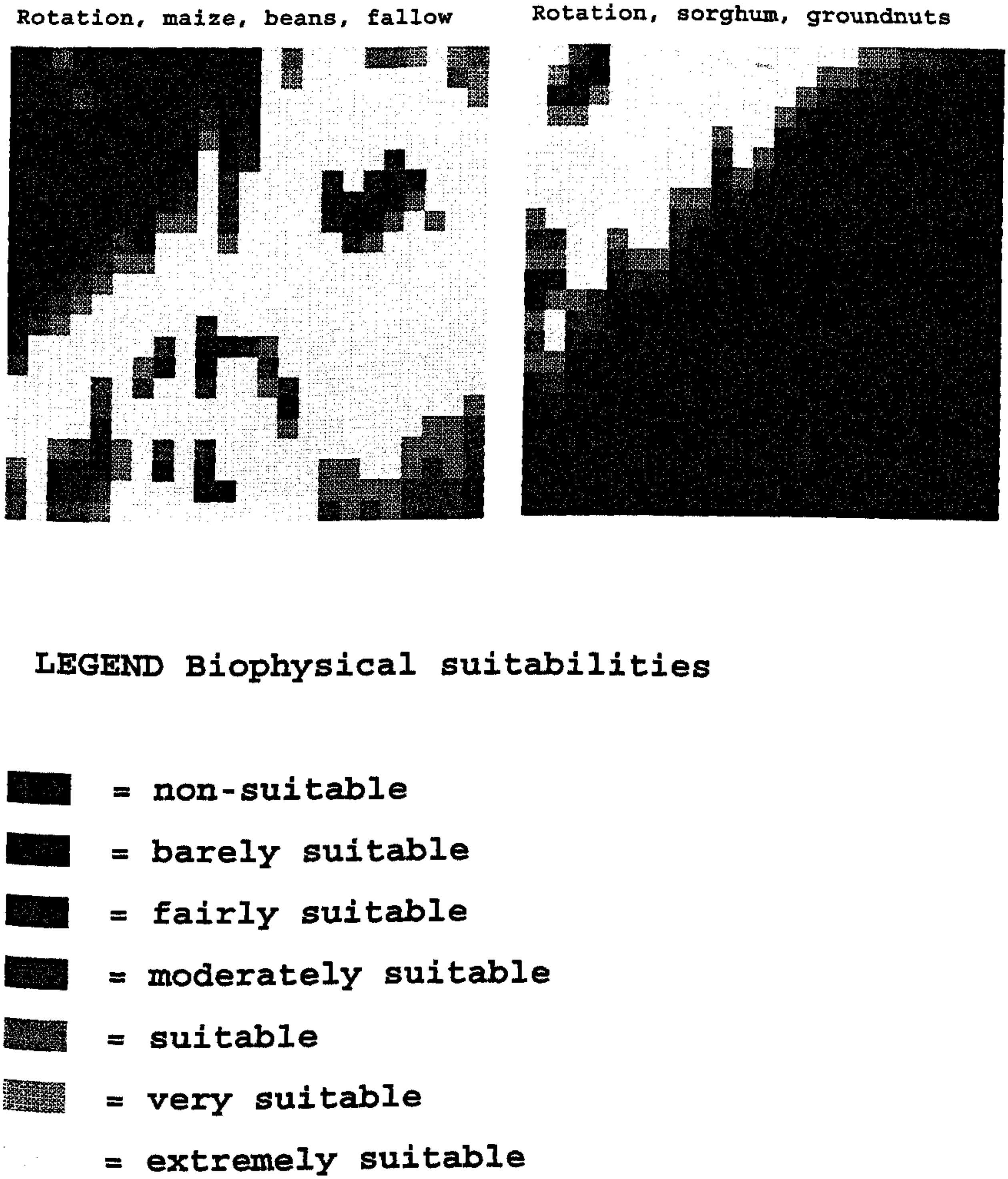
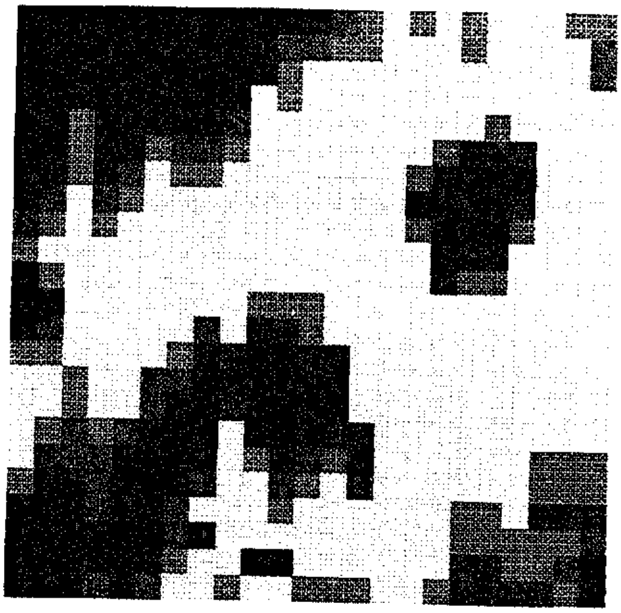
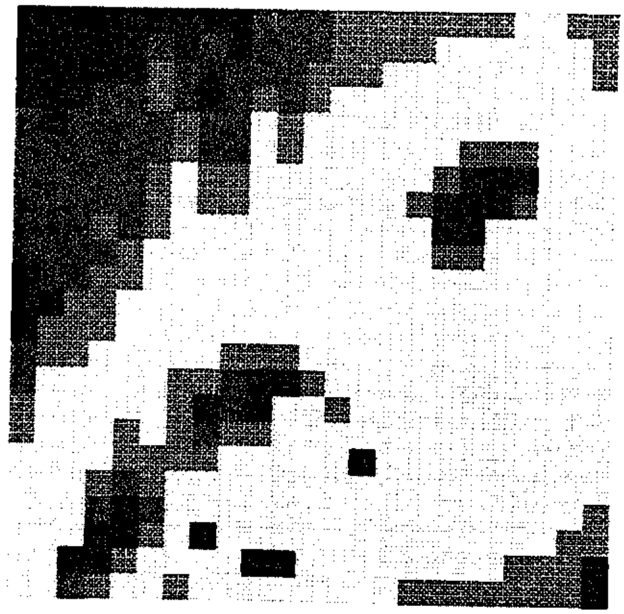


Fig. 4.1 Suitability maps of the simulated region for the 10 land use types.

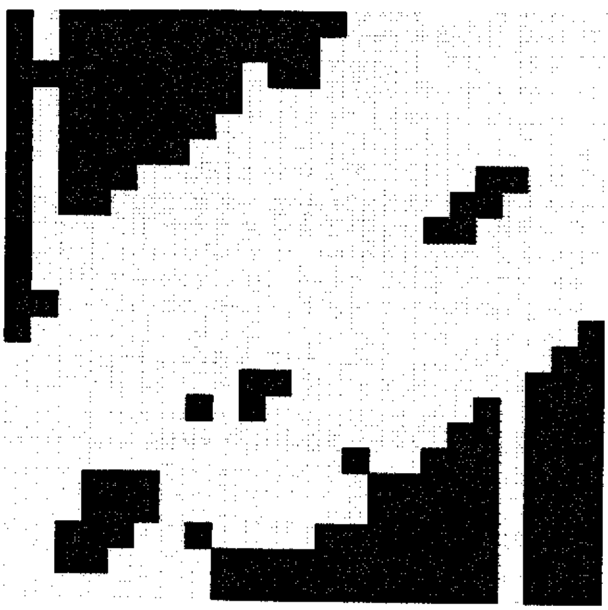
Cassava



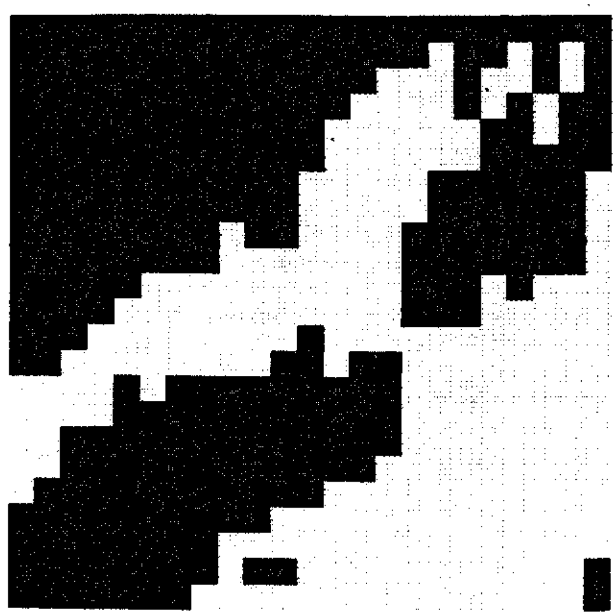
Range land



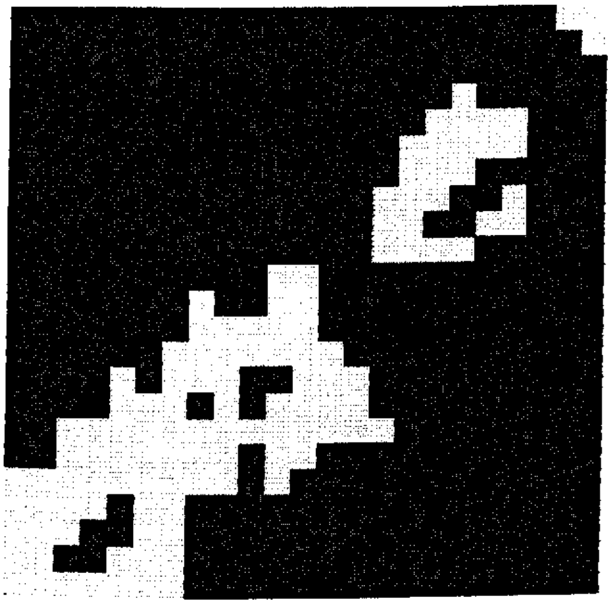
Pinapple plantation



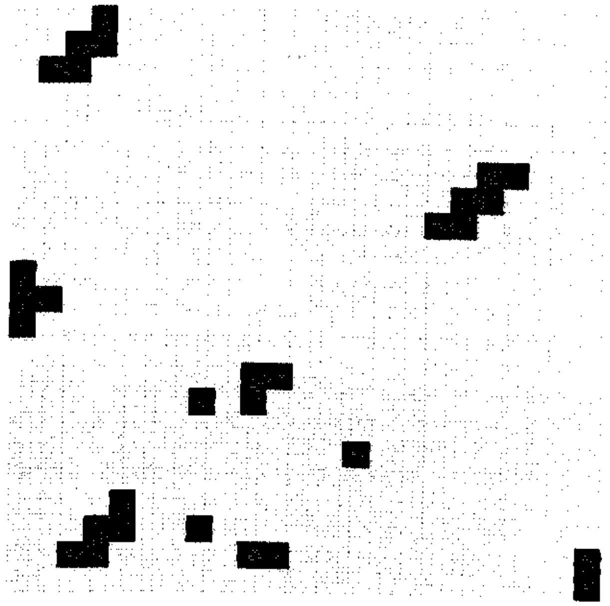
Banana plantation



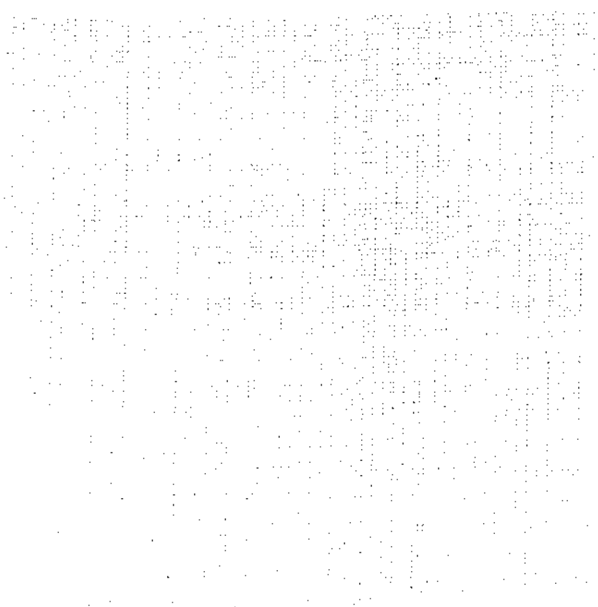
Tea plantation



Natural vegetation



No agricultural use



Town

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).

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 and barely to extremely suitable. The suitability maps (Fig. 4.1) indicate various initial suitabilities for each land use type. To create sufficiently diverse conditions, the selected suitabilities only partly overlap each other (Fig. 4.1). 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. 4.2)

c) Initial distribution of land use types is shown in Fig. 4.2. 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).

Table 4.1

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 4.2

Vegetation cover during growing season on monthly basis without bio-physical 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
LU 1	10	30	80	100	100	0	0	5	10	30	50	80	0	10	20	40	45	50	60	65	67	70	71	73
LU 2	10	40	50	80	0	0	5	15	30	50	90	90	10	40	50	80	0	0	5	15	30	50	90	90
LU 3	10	30	50	80	75	70	75	80	90	90	90	95	95	95	95	95	95	95	0	5	10	20	25	30
LU 4	100	100	100	100	100	95	95	95	100	100	100	95	100	100	100	100	100	95	95	95	100	100	100	95
LU 5	10	30	60	65	65	65	65	70	80	85	85	85	90	90	90	90	90	90	90	90	0	5	10	15
LU 6	40	60	80	100	100	100	100	100	100	100	100	100	40	60	80	100	100	100	100	100	100	100	100	100
LU 7	100	100	100	95	100	100	100	95	100	100	100	95	100	100	100	95	100	100	100	95	100	100	100	95
LU 8	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
LU 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LU 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

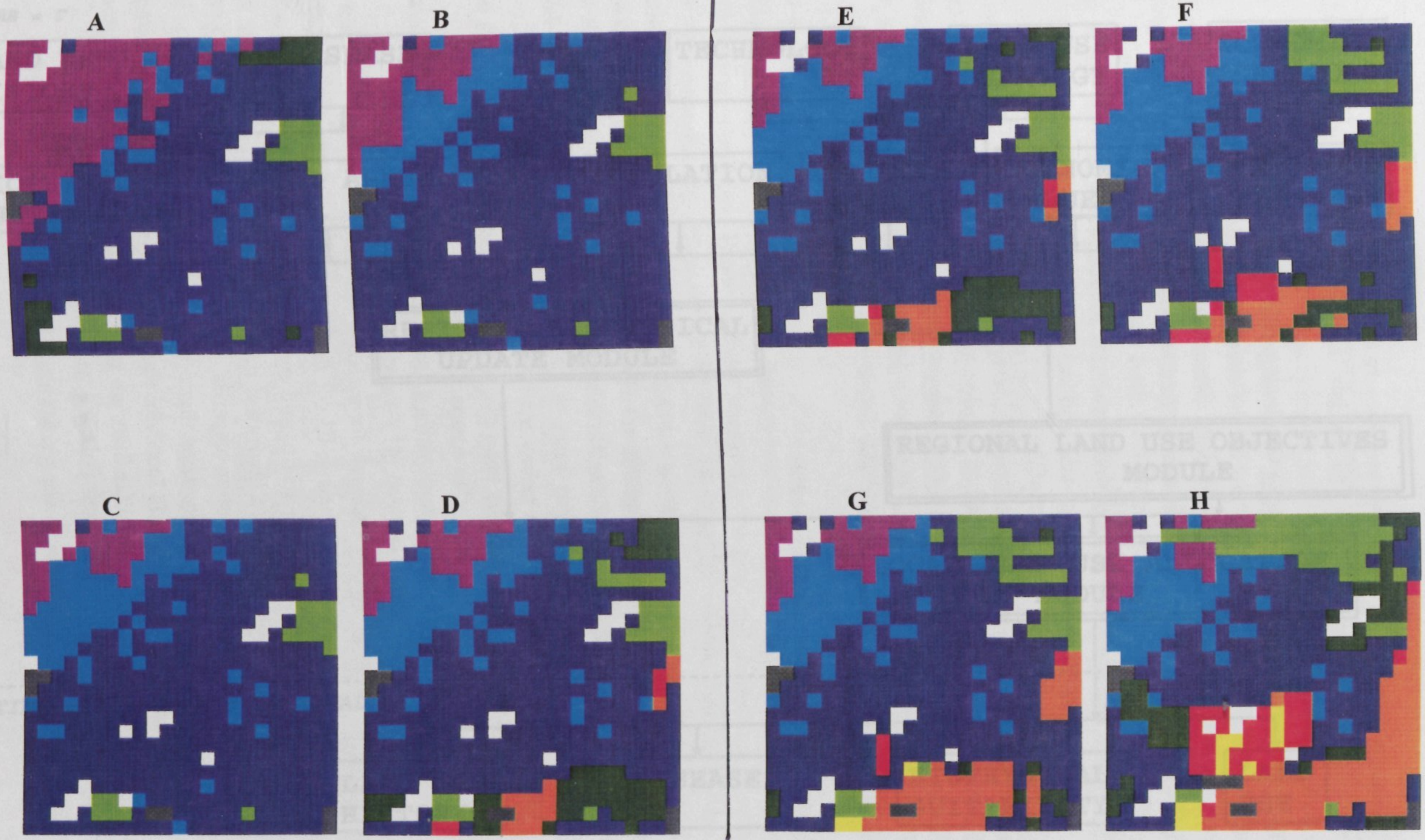


Fig. 4.5 Land use outputs of the described scenario.

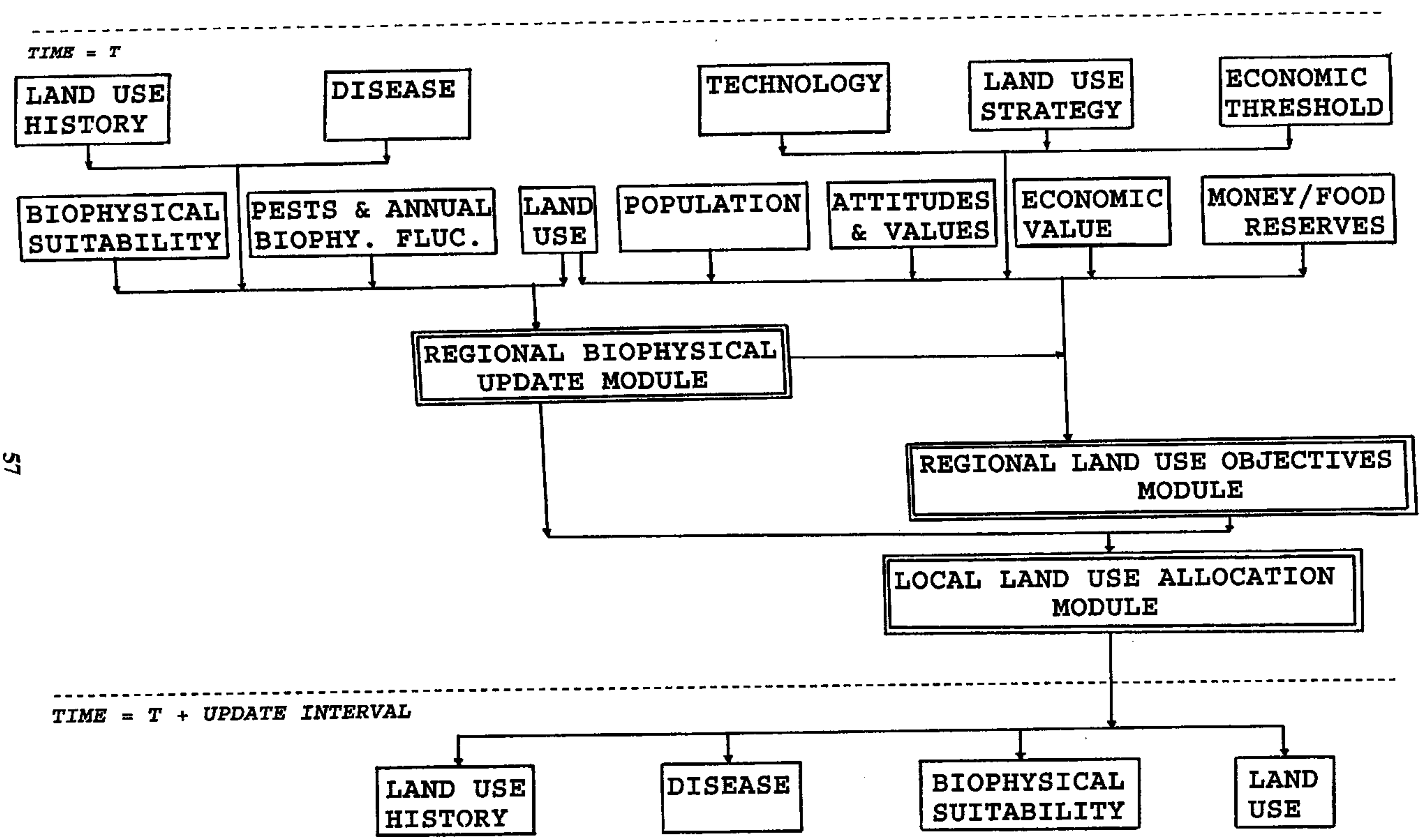


Fig. 4.3 Overview flow chart of the three modules within the CLUE model.

4.5 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. 4.3):

1) a regional biophysical update module, simulating effects of biophysical processes and factors 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. 4.4).

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

4.6 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 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 due to climatic dynamics or pests. It is assumed that yield levels can fluctuate up to ± 80% 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 bio-physical 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.

4.7 Land use objectives module

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

Table 4.3
Relative values and preferences of the different land use strategies.

LU no.	Rel. values LU per strategy strat.1	strat.2	strat.3	strat.4	Rel. preference for LU per strategy 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

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.

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.

4.8 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. 4.4) are applied. For food crops (LU 1, 2, 3, 4) an allocation procedure causing spiral wise growth of land use concentration regions is applied, while commercial LU types (LU 5, 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 <u>local</u> 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.

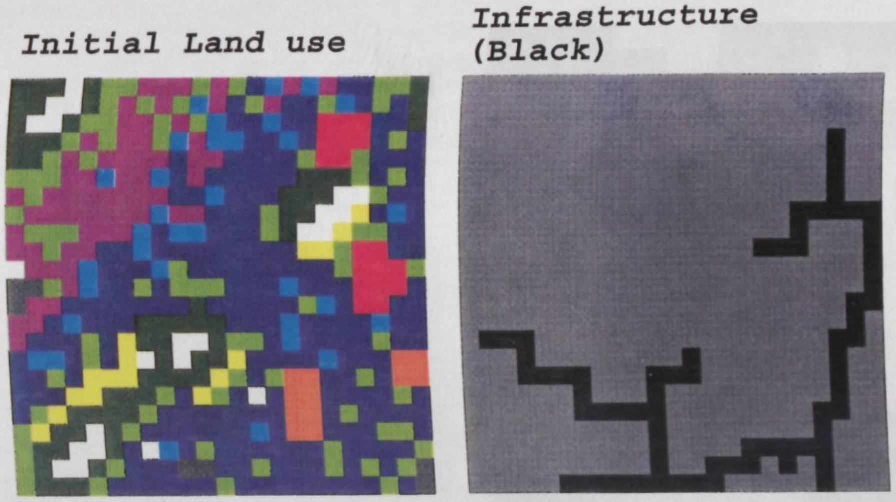
h: Existing land use and the proposed new land use are compared and evaluated. The 'value' of the actual and proposed land use are determined and compared. This 'value' depends on the yield level, the applied land use strategy and the grid biophysical suitabilities for the different land uses.

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 a it has not reached its minimum economical age. During the LU allocation procedures each grid unit is evaluated individually.

4.9 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 bio-physical 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 Tab. 2 and Fig's 4.1 and 4.6.

Fig. 4.2 Initial land use and infrastructure in the simulated imaginary region.



LEGEND Land use simulation (CLUE)

- = Rotation, maize, beans, fallow
- = Rotation, sorghum, groundnuts
- = Cassava
- = Range land
- = Pinapple plantation
- = Banana plantation
- = Tea plantation
- = Natural vegetation
- = No agricultural use
- = Town

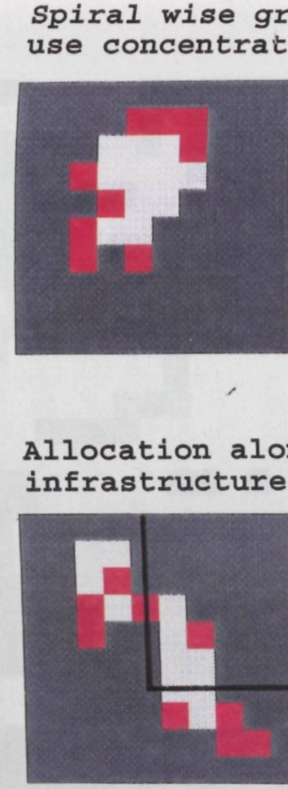


Fig. 4.4 The principles of the two land use allocation procedures.

Legend Allocation Scheme

- = Non-LUx land use
- = New allocated land use LUx
- = actual land use concentration area of LUx
- = Infrastructure

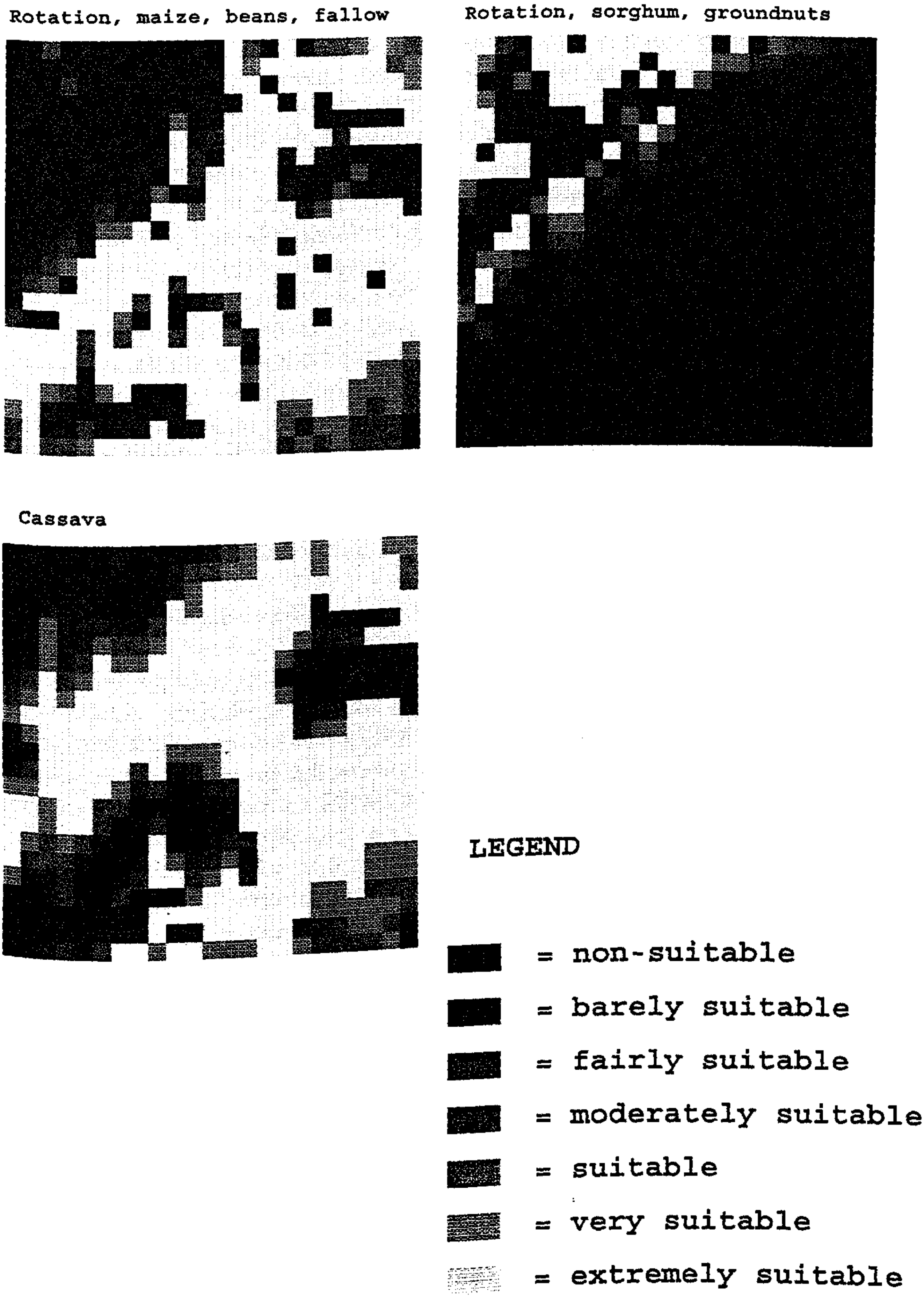


Fig. 4.6 Output of land suitabilities after the described simulation.

4.10 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. 4.2) 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. 4.5 a). 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. 4.5 b & 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. 4.5 d & 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. 4.5 e & 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. 4.5 g). 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. 4.5 g). After several years a remedy for the pineapple disease is available, causing a reintroduction of pineapple plantations within the area (Fig. 4.5 h). Remote areas, not directly assessable by the main infrastructure (Fig. 4.2), 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. 4.5 h) 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 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. 4.5h and 4.6). 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. 4.6. A comparison with the initial suitabilities in Fig. 4.1 demonstrates the long term effects of none sustainable land use systems.

4.11 General discussion and conclusions

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\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.

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.

CHAPTER 5:

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

By: A. Veldkamp and L.O. Fresco

5.1 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 yet 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 analysis 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 (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 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

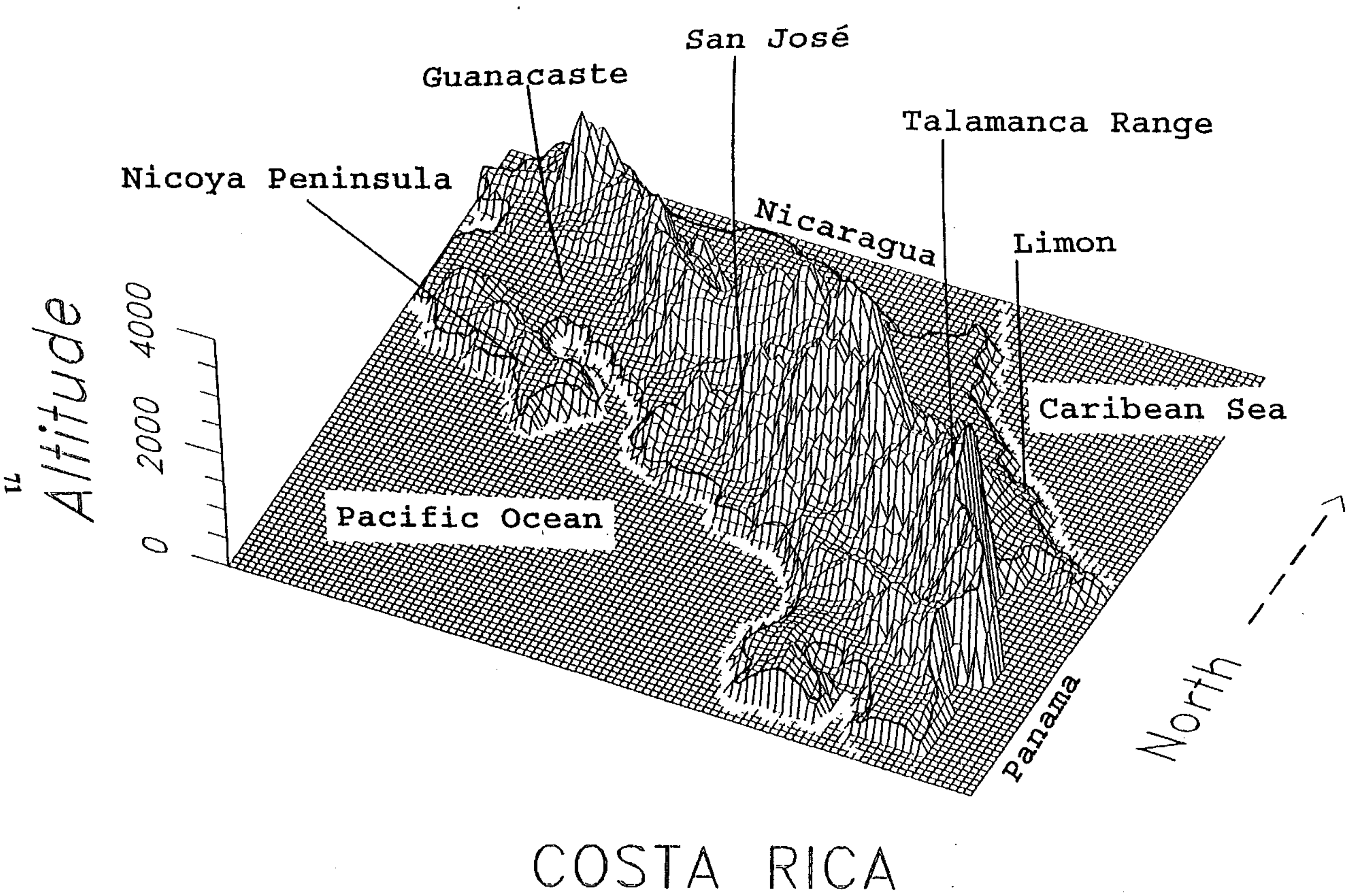


Fig. 5.1 Costa Rica, some cities and regions.

other domains. Scale as well as thematic limitations put strong constrains 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, in press, see also chapter 4). 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.

The georeferenced gridded data Costa Rica data (Fig. 5.1)(0.1° or 6' *geographical* grid, approx 7.5 * 7.5 = 56.25km^2 at the Equator) used in this modelling study were derived from the population and agronomic census data for Costa Rican districts (DGEC, 1976a, 1976b, 1987a, 1987b), the preliminary atlas of Costa Rica (Nuhn, 1978) and from climate maps (Herrera, 1985).

5.2 Land use/cover drivers in Costa Rica

In Chapter 3 we described to what extent and how the distribution of Costa Rican land 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 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.

5.3 Model description of CLUE-CR

Model type

The CLUE-CR model was based on the CLUE prototype model (Veldkamp and Fresco, in press) 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 seconds 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.

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 agricultural and none agricultural uses and covers like secondary vegetation, towns, roads, bare rock etc.

Overall assumptions in CLUE-CR:

a) 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.

b) Agriculture is the main employment and income generator in the rural areas of Costa Rica.

c) 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.

d) Land use changes occur only when biophysical and human demands can not be met any more through existing land uses.

e) The total land cover consists of five different categories (ARA, PER, PAS, NAT, RES) only, their sum in each grid being always 100%.

f) By incorporating reserves (food and/or money) for two years, seasonal and annual yield fluctuations have no direct effect on the land use changes.

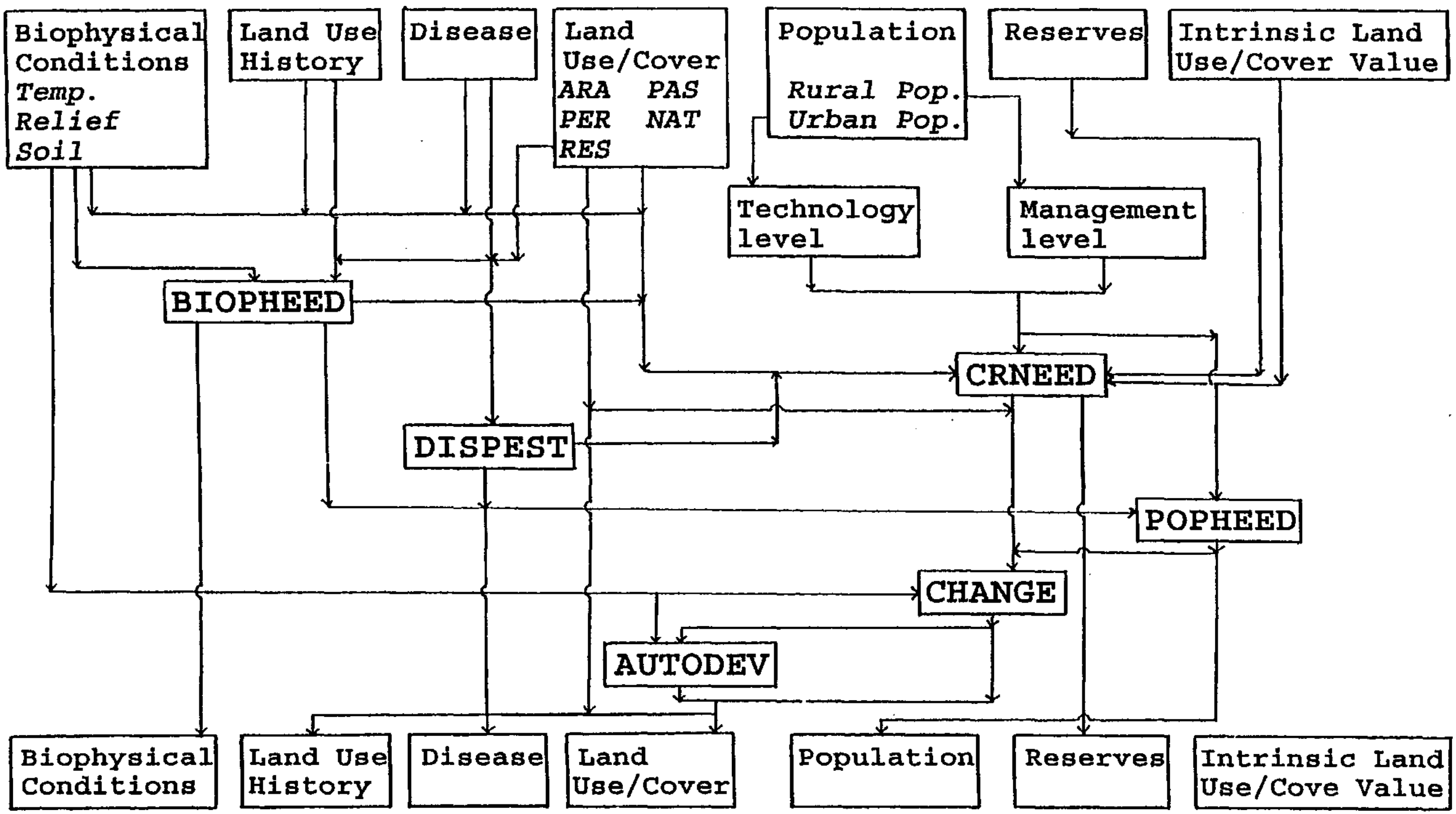


Fig. 5.2 Flow chart of the CLUE-CR model.

Table 5.1 Schematic description of the CLUE-CR procedures.

Procedure	Description
CRNEED:	Determines a need at the *national* level for new areas with certain land uses.
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 effects on the local rural/urban population.

Model inputs

For *each grid cell* CLUE-CR requires the following data: Altitude and/or Temperature, Relief, Soil drainage, Rural population, Urban population, % Permanent crop cover, % Arable land cover, % Pastures and range land cover, % Natural vegetation cover, % Residual group cover, Change rate 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.

Schematic overview of modelling sequence in CLUE

CLUE-CR has several different procedures (Tab. 5.1) 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. 5.2):

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 random annual fluctuation in cover yields is introduced to simulate temporal changes in biophysical conditions (climate). These changes range between minus 60% and plus 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.

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 (Chapter 3) demonstrated that each land use/cover regression model has a maximum scale-dependent model fit. 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.

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 conditions, i.e. independent of the regional and national demands and surpluses. These autonomous changes may have an aggregated (bottom up) effect on the regional and national scales.

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 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.

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.

Model Drivers

Two different land use/cover drivers operate within the model:

A: Changes in population (urban and rural) which is simulates both as input (POPGROWTH) and as feedback effect of land use/covers.

B: 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).

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.

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 biophysical regions/zones of Costa Rica (Fig. 5.3).

Region 1: The hot and humid region, comprising the Atlantic zone (northeast) and Osa, Golfito (south).

Region 2: The hot and dry region, comprising the coastal Pacific zone.

Region 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).

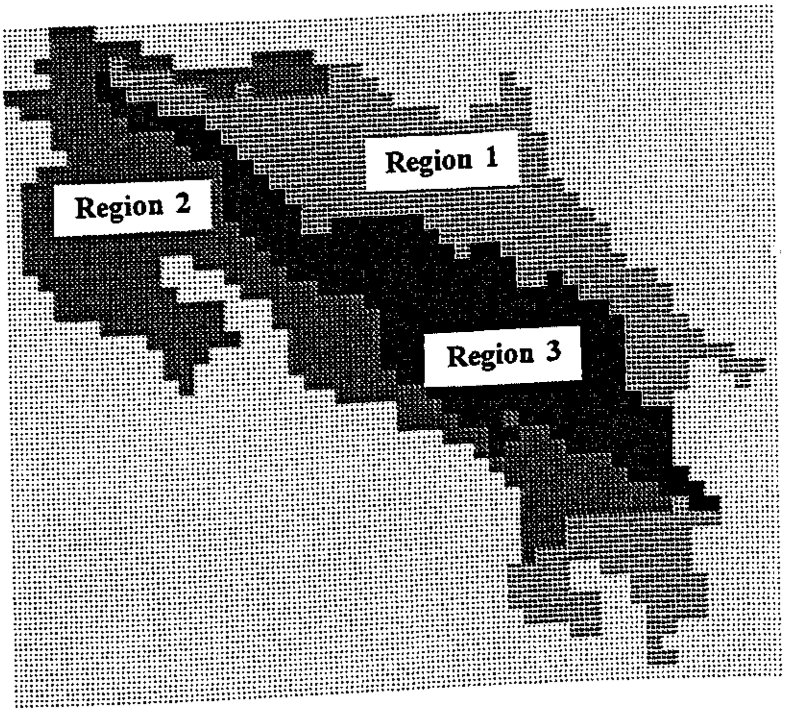


Fig. 5.3 **The three selected agro-ecological regions in Costa Rica. Region 1: hot and humid; region 2: hot and dry; Region 3: cool and humid.**

5.4 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 (chapter 3). 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.

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.

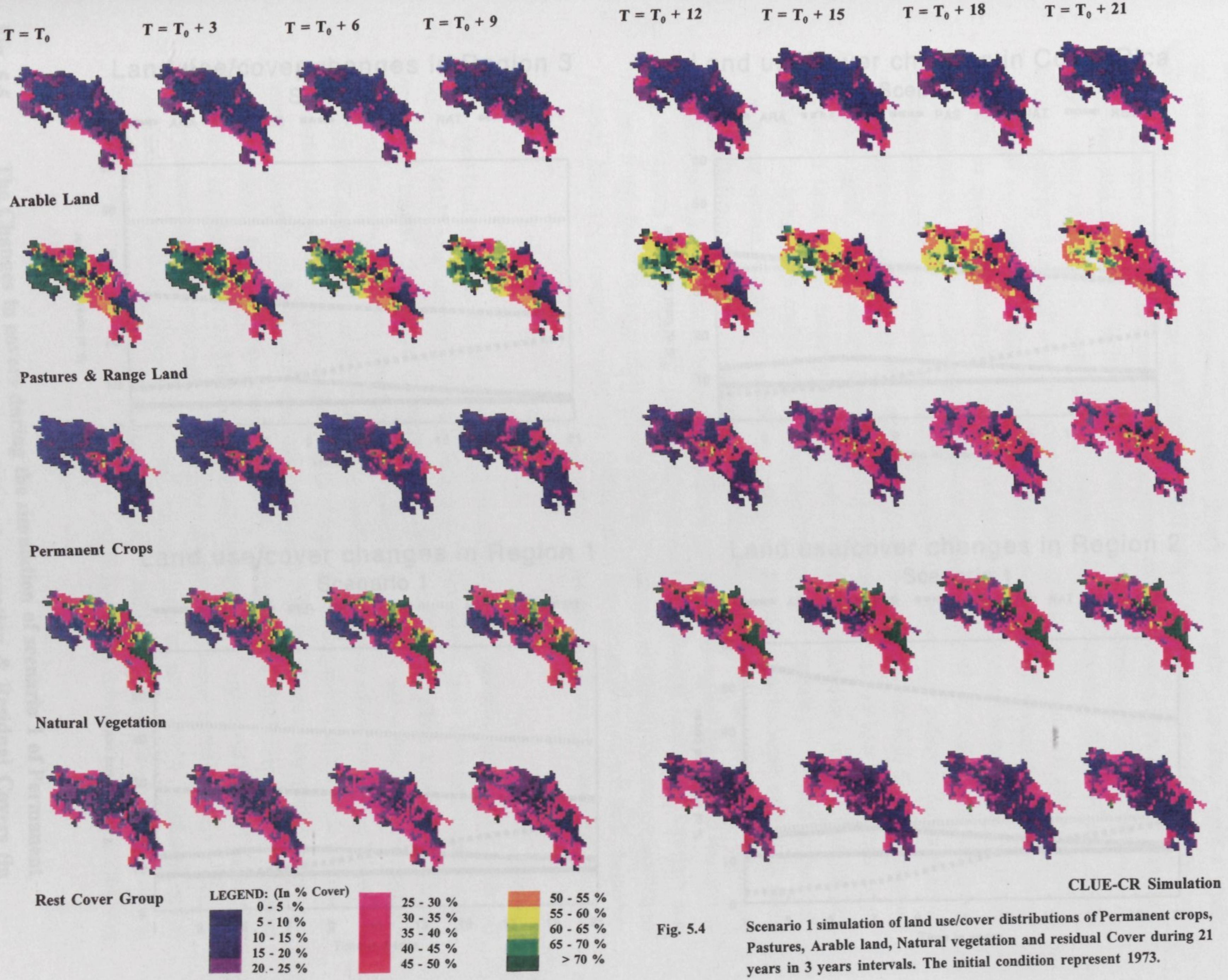


Fig. 5.4 Scenario 1 simulation of land use/cover distributions of Permanent crops, Pastures, Arable land, Natural vegetation and residual Cover during 21 years in 3 years intervals. The initial condition represent 1973.

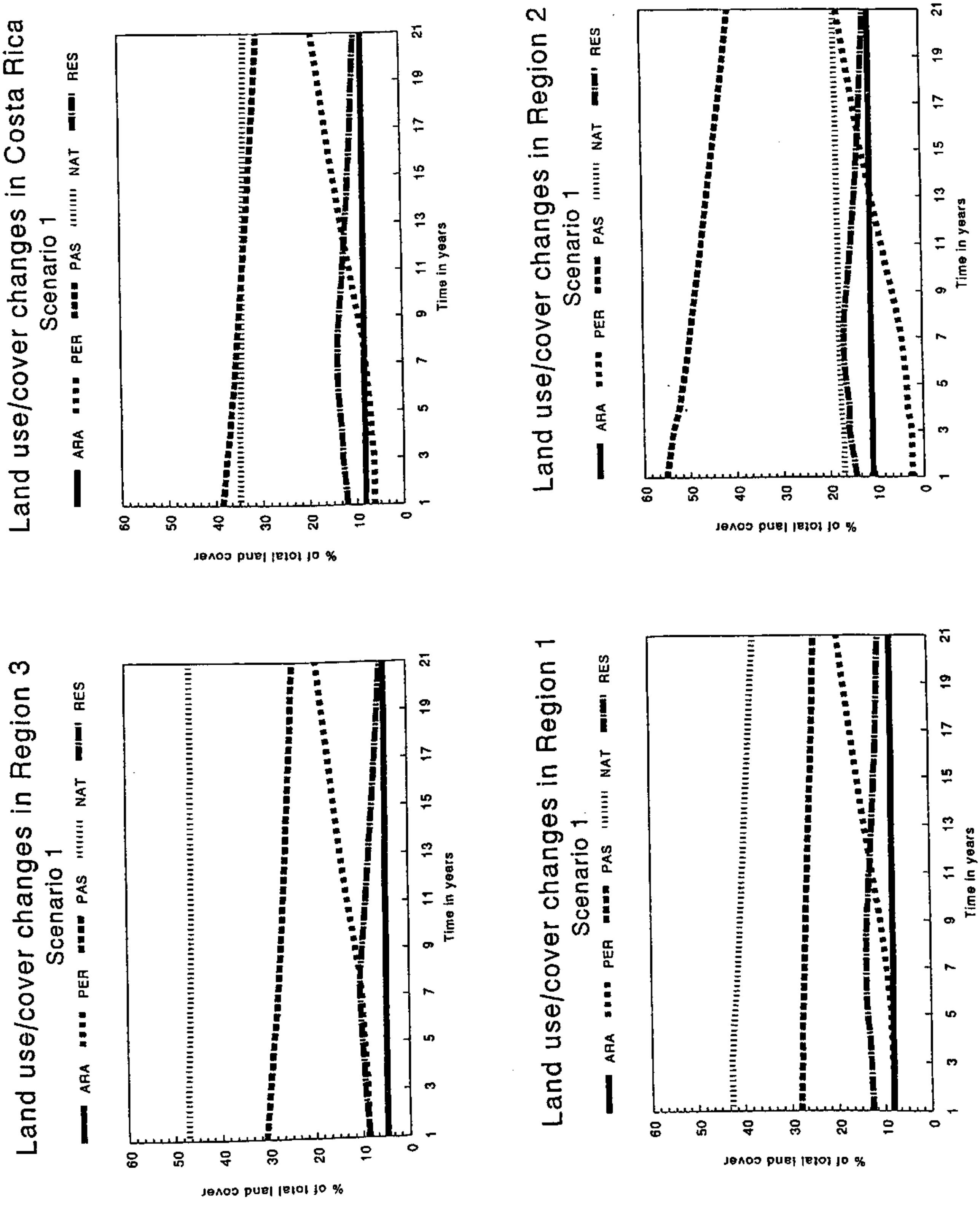
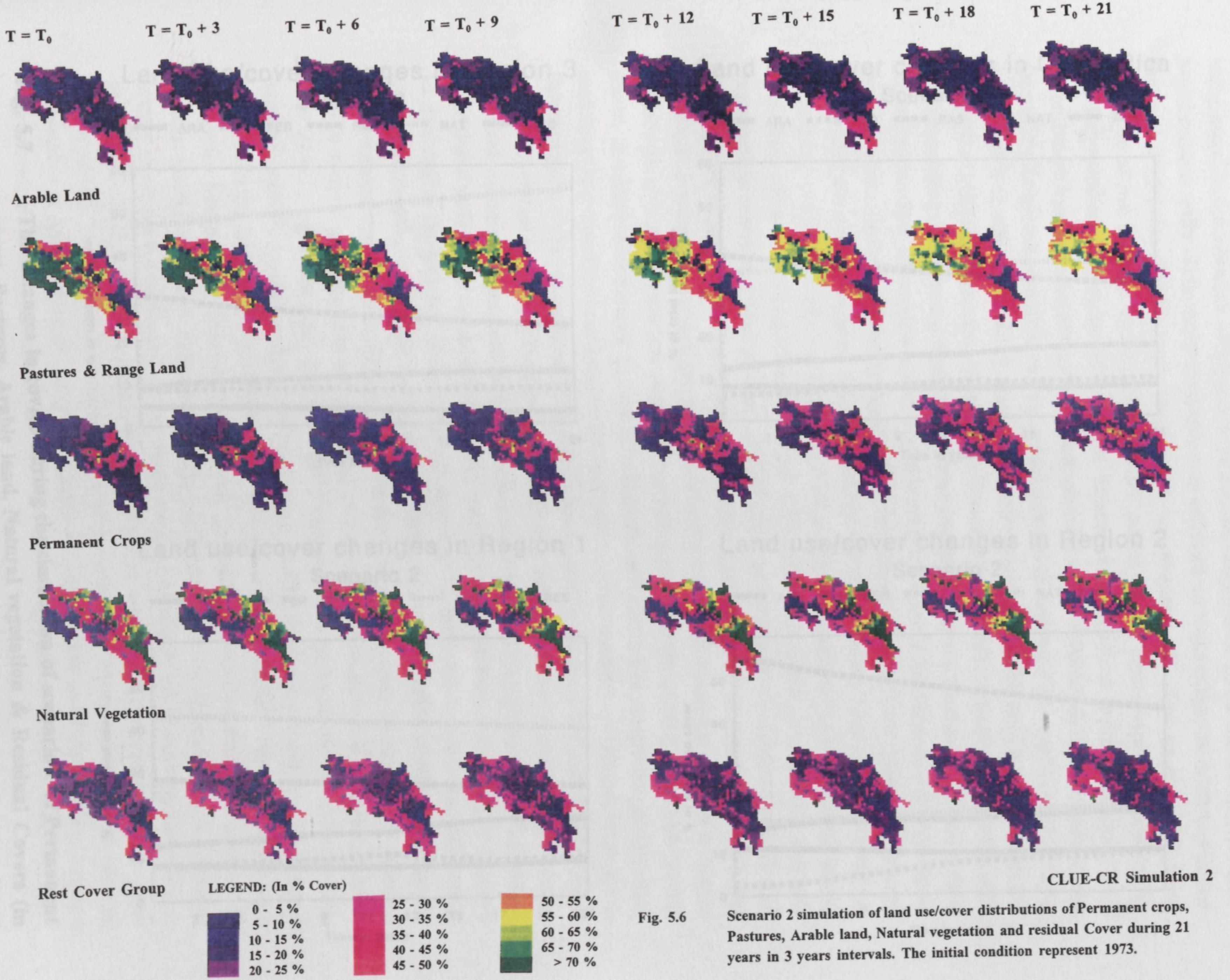


Fig. 5.5 **The Changes in covers during the simulation of scenario 1 of Permanent crops, Pastures, Arable land, Natural vegetation & Residual Covers (in % total cover) aggregated to the three regions of Fig. 3 and Costa Rica.**

In Fig. 5.4. the changing five land covers are given in three years 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. 5.3. and Costa Rica (Fig. 5.5). Region 1 (hot & 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; chapter 3). 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.

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, 1993). 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.



CLUE-CR Simulation 2

Fig. 5.6 Scenario 2 simulation of land use/cover distributions of Permanent crops, Pastures, Arable land, Natural vegetation and residual Cover during 21 years in 3 years intervals. The initial condition represent 1973.

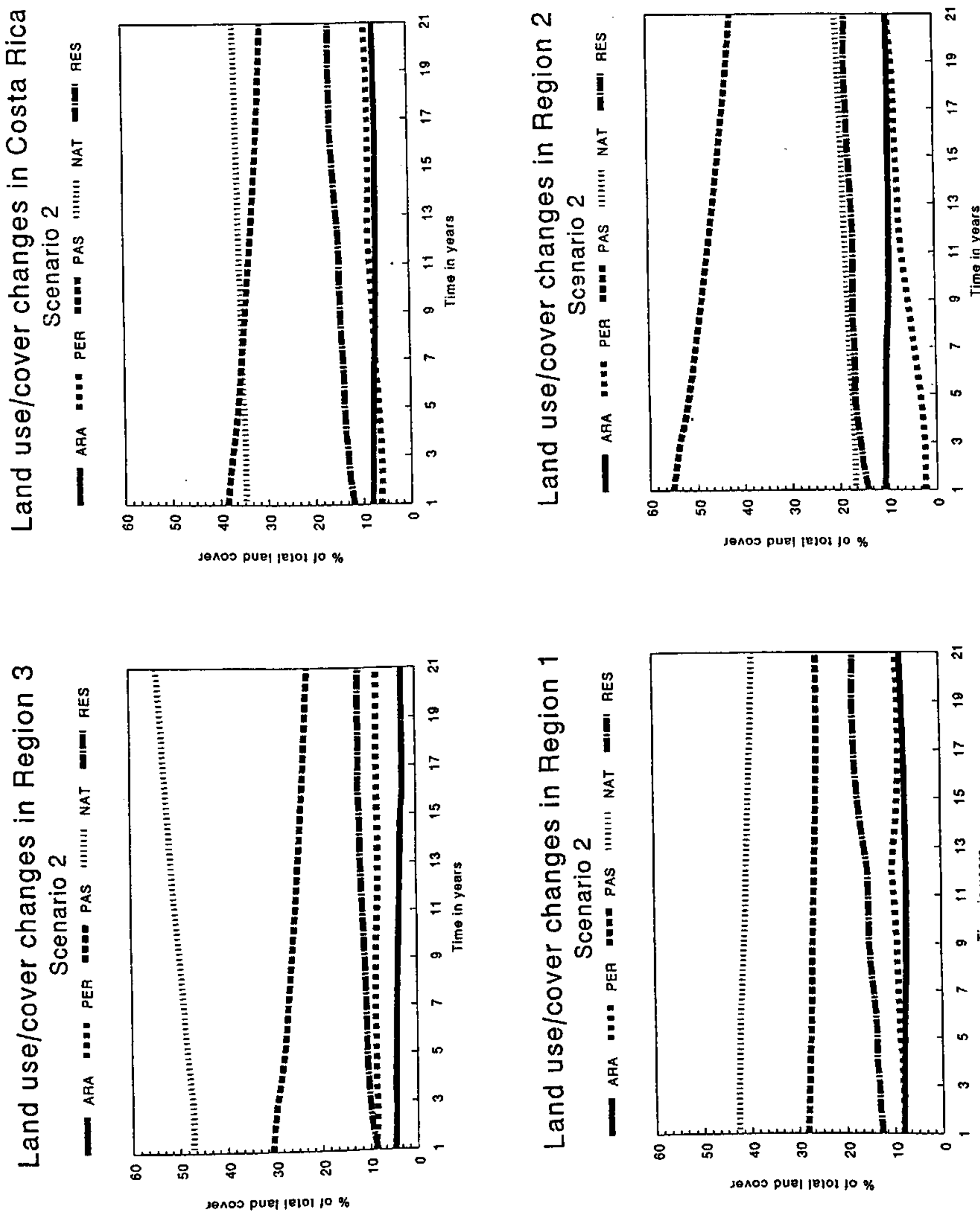


Fig. 5.7 **The Changes in covers during the simulation of scenario 2 of Permanent crops, Pastures, Arable land, Natural vegetation & Residual Covers (in % total cover) aggregated to the three regions of Fig. 3 and Costa Rica.**

In Fig. 5.6. the changes of the five land covers are given at three years 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 know 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 knows 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 considerable 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. 5.7). Region 1 (hot & 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 in to 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 an other 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. 5.7).

5.5 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. 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 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 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.

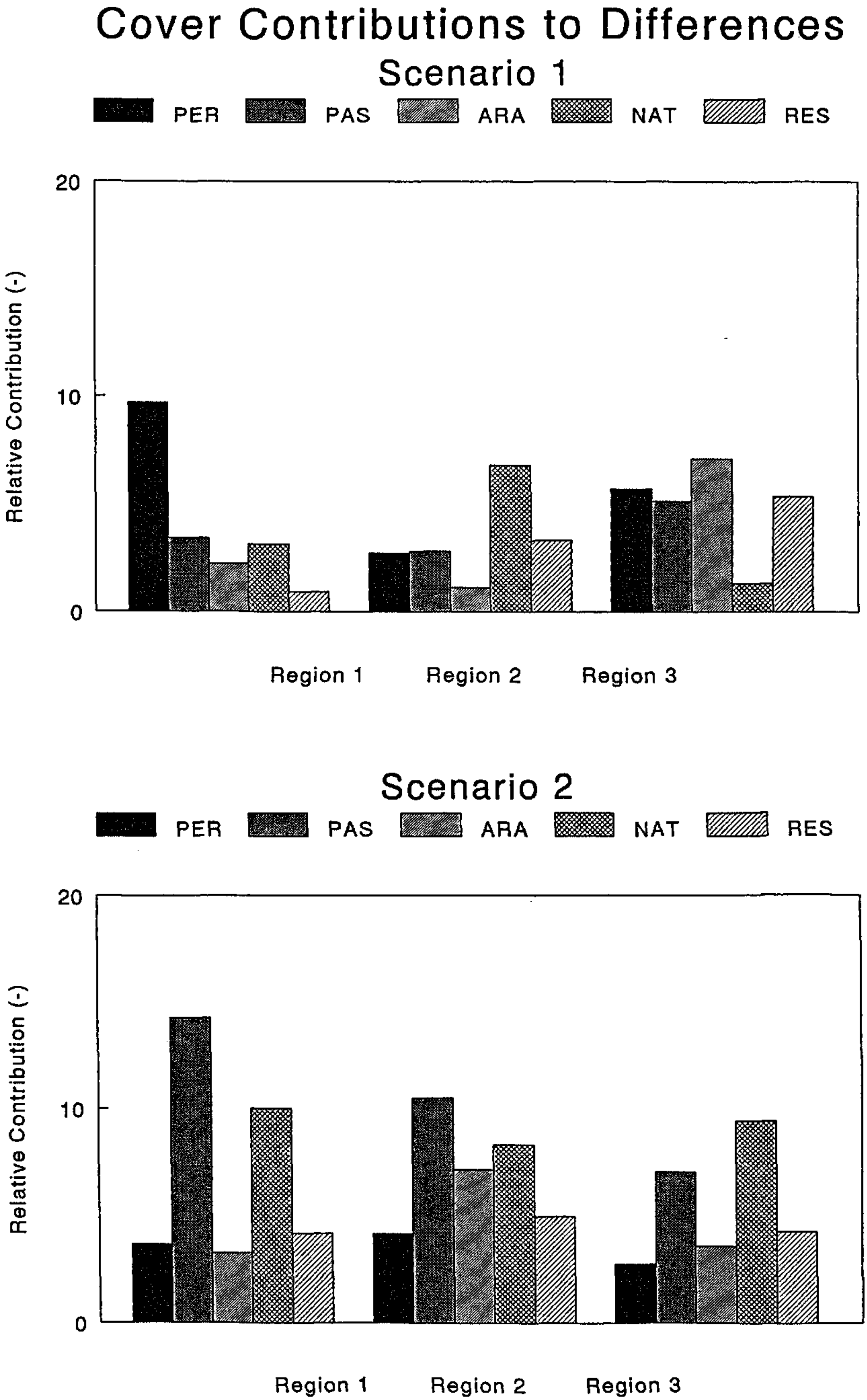


Fig. 5.8 **The relative contributions of the different covers to the maximum difference in cover between simulations and the 1984 data.**

Table 5.2 Absolute differences (in % region cover) between 1984 data and scenario 1 and 2.

Difference (in % total region cover) between 1984 data and scenario 1

Cover type:	PER	PAS	ARA	NAT	RES	Total
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

Difference (in % total region cover) between 1984 data and scenario 2

Cover type:	PER	PAS	ARA	NAT	RES	Total
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

Model sensitivity and tuning

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.

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 (Tab. 5.2). 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 is 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. 5.8). 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 robustic and specific enough to describe the general multi-scale dynamics of land use/cover system.

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 b) 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 (GCM's) 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 attempted 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 American 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). 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) an operational and realistic Central American land use/cover change model may 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.

CHAPTER 6:
Conclusions and recommendations

By A. Veldkamp and L.O. Fresco

The project resulted in the development of concepts for handling the highly dynamic features of land use change and its drivers for a small country (Costa Rica) at different spatial scales. An analysis of Costa Rican land use/cover system distribution and their dynamics at six different spatial scales (Chapter 3) demonstrated that the human/biophysical dimensions of land use/cover systems are scale dependent. Each land cover has its own specific set of human and biophysical scale related drivers. Most important Costa Rican drivers or their related proxies where urban and rural population, agricultural labour force, infrastructure, relief, soils, and climate. Most changes in land use from 1973 to 1984 were related to changes in population density and their distribution and confined to certain biophysical conditions. The reconstructed drivers were simulated and integrated within a dynamic model framework, Conversion of Land Use and its Effects (CLUE) (Chapter 4). The CLUE approach is was applied successfully for Costa Rice using 913 (0.1°*0.1°) grids (chapter 5).

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 multi-scale land use/cover change models. CLUE allows geographically explicit modelling of the effects of changing demographical and biophysical driving forces or their proxies on land use/cover changes. 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 constrains to scale CLUE 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.

Future research

Within the land cover model (LCM) of IMAGE 2 Costa Rica consists of 18 (0.5°*0.5°) grids. Both models have limited socio-economic (e.g. effects of urban/rural exchange and affluence) and biophysical feedbacks (e.g. effects of degradation, over use and irrigation) and currently operate at different scales. It was already discussed in chapter 3 that processes involved in land cover and land use change operate across many spatial and temporal scales (Fresco and Kroonenberg, 1992; Turner et al., 1993). Any attempt to model human (demographic and socio-economic) and biophysical drivers of global land use/cover can thus only be successful when an integrated modelling effort is carried out at various (≥ three scales, Odum, 1983) scales. We propose therefore to apply and combine the CLUE and IMAGE methodology to model land use/cover dynamics at various scales, allowing up and down scaling of these dynamics. This effort will gain us a more comprehensive perception of the model performances and the relations between driving forces, scale and land use dynamics and socio-economic feedbacks. Only in this way quantitative assessments and meaningful integrations with socio-economic models can be made. To increase the realistic performance of land use dynamics it should be attempted to incorporate effects of urban rural migration, irrigation and land degradation in a more realistic way.

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