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Reconstructing Land Use Drivers and their Spatial Scale Dependence for Costa Rica (1973 and 1984)

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ABSTRACT

Costa Rican land use and cover (in 1973 and 1984) were investigated using a nested scale analysis. 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. In Costa Rica two land use/cover trends between 1973 and 1984 can be discerned: (a) intensification in the urbanized Central Valley and its surroundings, where agriculture is extended to steeper and less favourable soils due to a high population density; and (b) land use expansion in remoter areas, where the extension of arable land and pastures increased at the cost of natural vegetation. This deforestation was not driven by land shortage. The 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. Copyright © 1997 Elsevier Science Ltd

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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, Turner *et al.*, 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 as 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 & 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 vice versa 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 investigated to what extent and how the distribution of Costa Rican land use/cover and its changes between 1973 and 1984 were related to biophysical and human factors at different spatial scales. Costa Rica was chosen as a case study because this country is well known for its great biophysical diversity (Holdridge, 1967; Gómez, 1986), has a rapidly 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 & Joyce, 1988; Harrison, 1991; Veldkamp *et al.*, 1992).

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 on 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 was no possibility of generalizing these models. We are thus confronted with two different scale properties that need to be taken into account: (a) each scale has its own specific units and variables; and (b) 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 & 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 by 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 socioeconomic 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. Socioeconomic 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 lose 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 can be compared without any spatial aggregation problem. Another advantage is that artificially gridded data can be aggregated into many different scales whereas data grouped in administrative boundaries, for example, can only be aggregated into a few predetermined scales. Costa Rica only allows aggregation from districts ($n = 419$) into cantons ($n = 80$), provinces ($n = 7$) and Costa Rica as a whole ($n = 1$). 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 therefore propose 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. Such an analysis, however, would require data covering considerable time spans, possibly up to 10^5 years to capture ecological evolutionary processes (see also Fresco & Kroonenberg, 1992).

MATERIALS AND METHODS

Data

The basic data used in this study were obtained from the population and agronomic census of Costa Rica (DGEC, 1976*a*, DGEC, 1976*b*; DGEC, 1987*a*, DGEC, 1987*b*) 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, relief and soils give a good representation of the biophysical conditions including climate variability (Herrera, 1985; Brenes & Saborio Trejos, 1994). Population data consist of rural population, urban population and agricultural labour force. 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) have a specific distribution within the country which changed between 1973 and 1984 (Fig. 1) (in percentage land cover). More detailed descriptions and maps of the used census and biophysical data are given in Veldkamp & Fresco (1995).

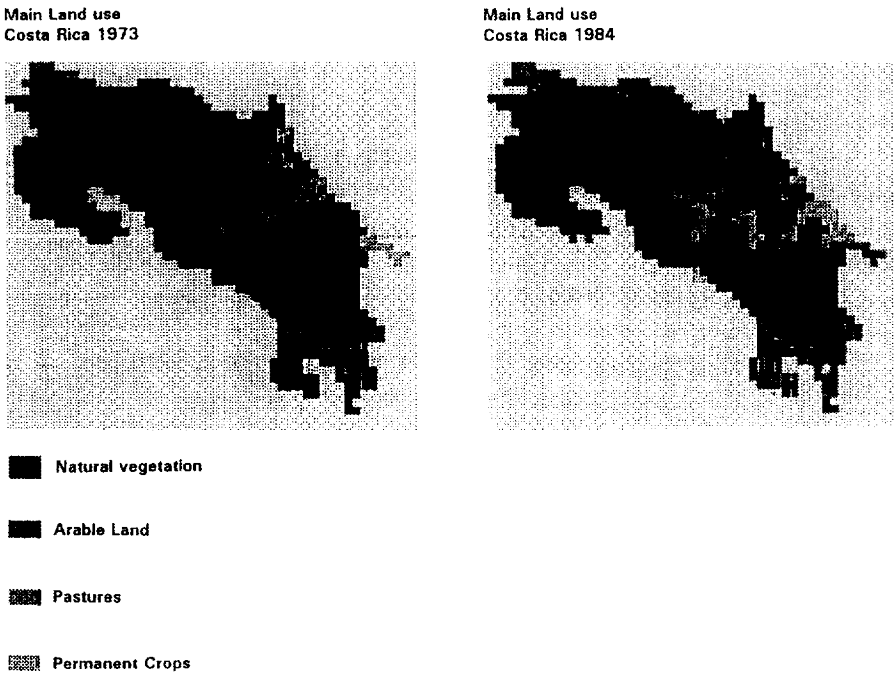

Fig. 1. Main land uses in Costa Rica in 1973 and 1984, derived from census data (see legend).

The census data were converted into grid cells. The selected minimum grid size (0·1° *geographical* grid, approximately 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.

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) and 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 contribute a valid value. Values are valid when they are created from 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 level = 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 a disadvantage that one excludes 'new' variables at the analysis of aggregated scales, which may lead to an incomplete system description. On the other hand, the model fit (coefficient of determination) will give a quantitative measure of the 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 behaviour. 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.

The methodology used is summarized in the flow diagram of Fig. 2.

RESULTS

Factor analysis

Factor analysis of the 1973 and 1984 data resulted in rather consistent factors explaining most variance (Table 1). The total variance in the 1973 data set can be described by four 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 vs. natural vegetation factor (factors 2 or 3); an independent biophysical factor (factors 2, 3 or 4); and a pasture vs. natural vegetation factor (factors 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 population is particularly interesting. At detailed spatial scales the population factor has no significant contribution at all, whereas at the more aggregated scales (scales 4, 5 and 6) it is related to the pastures vs. natural vegetation or arable land vs. natural vegetation.

The variance within the 1984 data set can also be described by four significant factors, explaining between 73% and 78% of the total variance.

The factors can be interpreted as: a population/permanent crop factor (factors 1 or 2); an arable land/secondary vegetation vs. natural vegetation factor (factors 2 or 3); an independent biophysical factor of altitude and relief (factors 2, 3 or 4) and a pasture/soil drainage vs. natural vegetation factor (factors 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

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

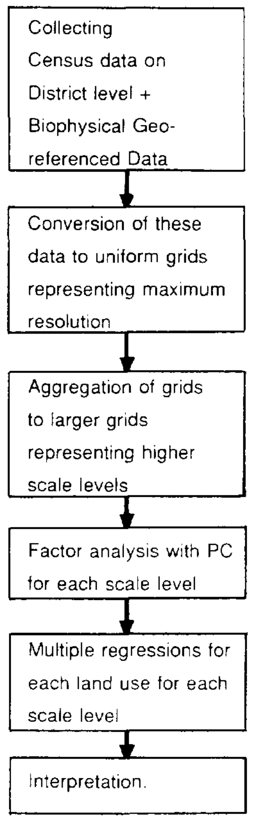

Fig. 2. Flow diagram of the working methodology used.

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 (Fig. 3, Fig. 4, Fig. 5 and Fig. 6). Only the models significant at the 0·05 level are plotted. As a result of the limited number of cases at the higher aggregated scales, the multiple regression models are not always significant.

Natural vegetation

Natural vegetation in 1973 and 1984 is reasonably well modelled with multiple regression (R^2 ranges from 25 to 65%) with the variables altitude, soil drainage, urban population and agricultural labour force displaying a

TABLE 1
Factor analysis

			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						
Factor 1:	PER	PER	PER	PER	PER	PER
	RUR	RUR	RUR	RUR	ARA	RUR
	URB	ALF	URB	ALF	RUR	ALF
	ALF		ALF		ALF	
Factor 2:	ARA	ARA	SOIL	RELIEF	ARA	SOIL
	-NAT	SEC	PAS	SOIL	-NAT	ARA
	SEC		-NAT	-ALTITUDE	SEC	-NAT
					URB	SEC
Factor 3:	SOIL	RELIEF	ARA	ARA	-RELIEF	RELIEF
	PAS	ALTITUDE	-NAT	SEC	ALTITUDE	-ALTITUDE
	-NAT		SEC			
Factor 4:	RELIEF	PAS	RELIEF	PAS	SOIL	PAS
	-ALTITUDE	NAT	-ALTITUDE	NAT	PAS	-NAT
				URB	-NAT	URB
			1984			
scales:	1	2	3	4	5	6
No. grids:	1	4	9	16	25	36

Table 1 — *continued*

Explained variance (% of total)						
Factor 1:	28.0	27.8	30.1	32.6	34.3	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						
Factor 1:	PER	PER	PER	PER	PER	PER
	RUR	RUR	RUR	RUR	ARA	PAS
	URB	URBALF	URB	ALF	ALF	ALF
	ALF	ALF	ALF			
Factor 2:	ARA	ARA	ARA	RELIEF	ARA	RUR
	-NAT	-NAT	-NAT	SOIL	-NAT	ALF
	SEC	SEC	SEC	-ALTITUDE	SEC	
Factor 3:	SOIL	SOIL	SOIL	ARA	SOIL	RELIEF
	PAS	PAS	PAS	-NAT	PAS	-ALTITUDE
	-NAT	-NAT	-NAT	SEC	-NAT	URB
Factor 4:	RELIEF	RELIEF	RELIEF	PAS	-RELIEF	PER
	-ALTITUDE	-ALTITUDE	-ALTITUDE	URB	ALTITUDE	ARA
					URB	SEC

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.

general and gradual increase of model fit with higher aggregated scales for both years (Fig. 3). 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) are especially interesting for the variables agricultural labour force and urban population, which display a relatively decreasing contribution at more aggregated scales, whereas 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 & Joyce, 1988; Veldkamp *et al.*, 1992). The negative contribution of the agricultural

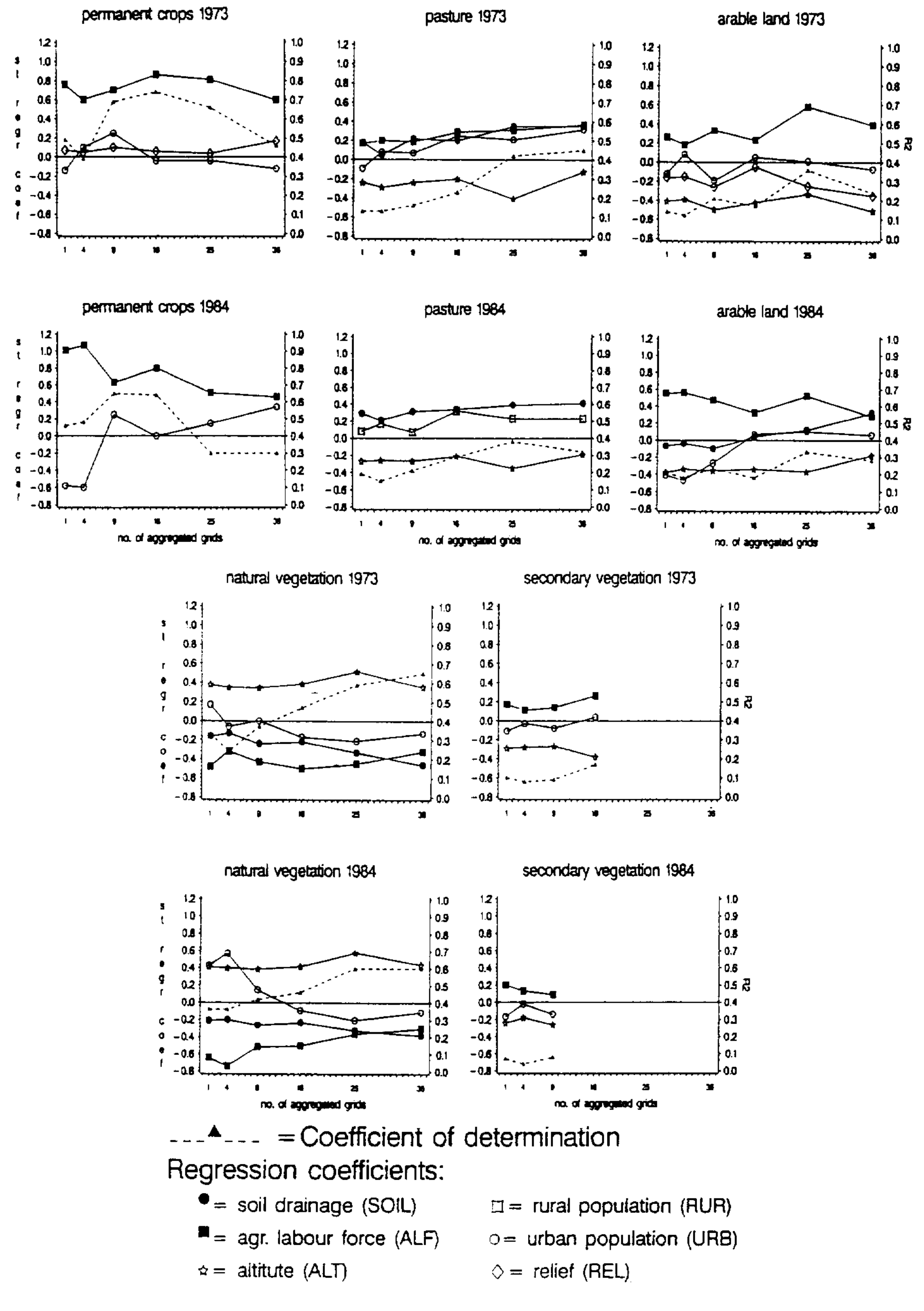

Fig. 3. Scale-dependent (scale in no. of aggregated 0·1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for permanent crops, pastures, arable land, natural vegetation and secondary vegetation in 1973 and 1984.

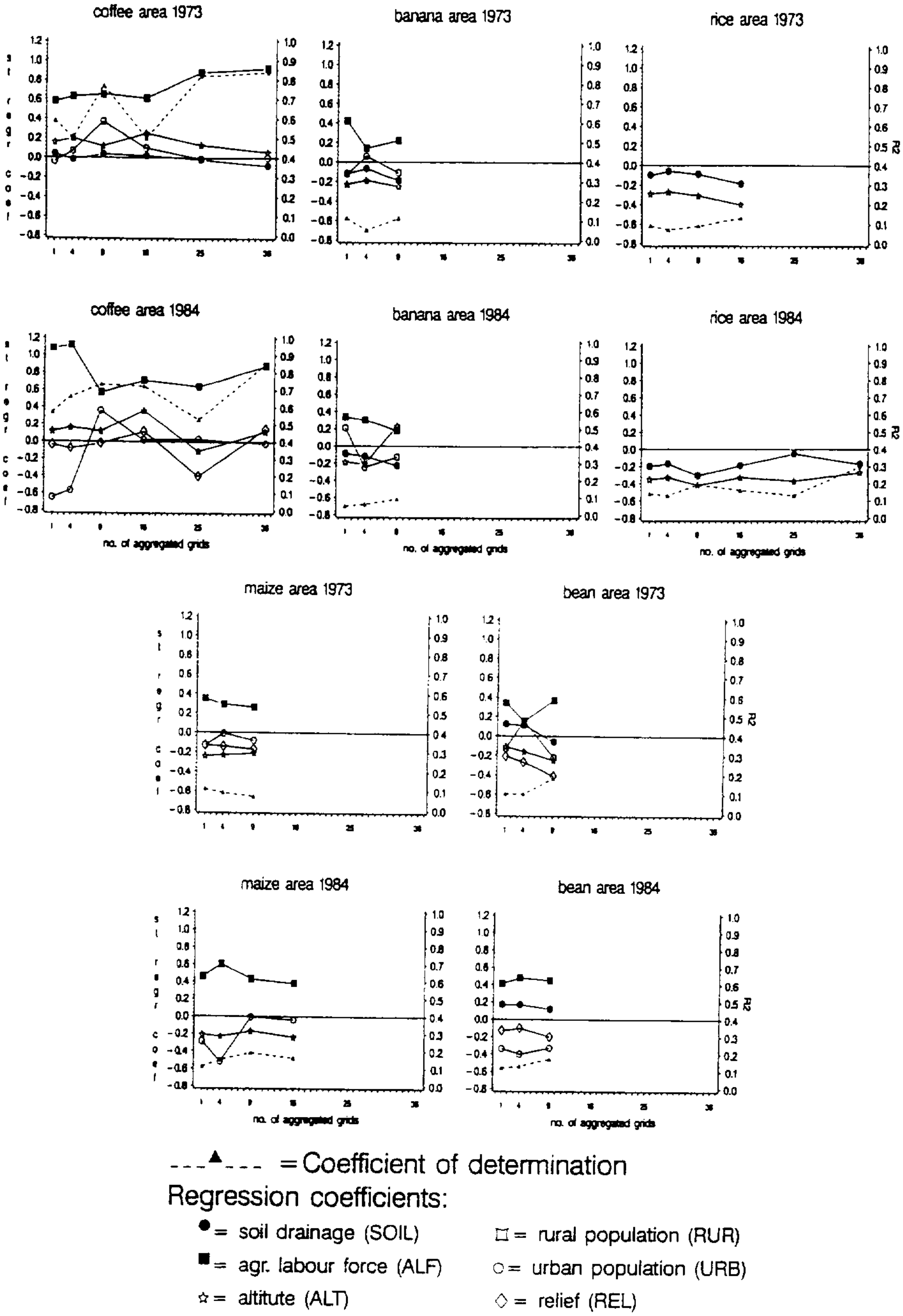

Fig. 4. Scale-dependent (scale in no. of aggregated 0·1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for the permanent crops: coffee and banana areas and for annual crops: rice, maize and bean areas in 1973 and 1984.

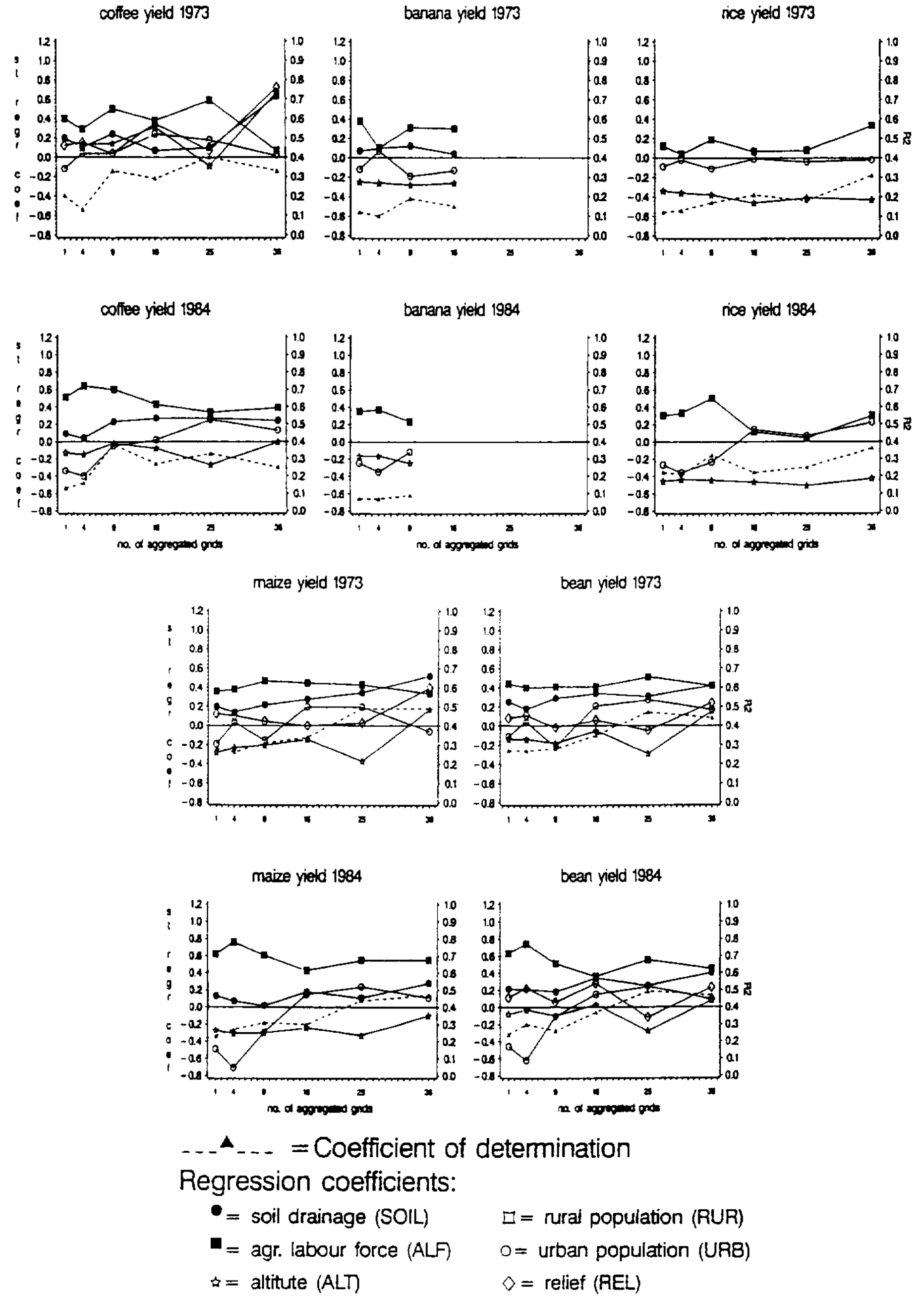

Fig. 5. Scale-dependent (scale in no. of aggregated 0·1° grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for the yields of coffee, rice, maize and beans in 1973 and 1984.

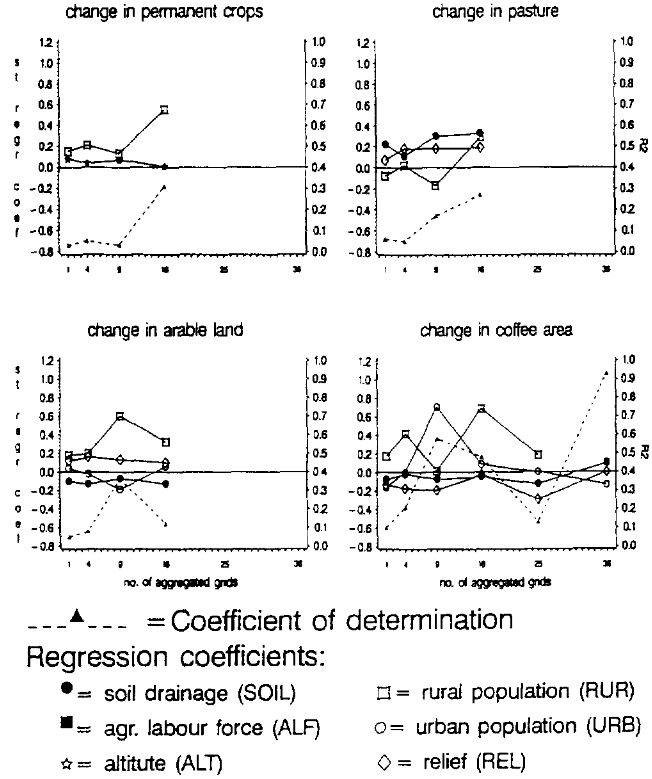

Fig. 6. Scale-dependent (scale in no. of aggregated $0{\cdot}1^{\circ}$ grids) regression models standardized regression coefficients (left axis) and model fit R^2 (right axis) for the changes in permanent crops, arable lands and pastures and coffee areas from 1973 to 1984.

labour force and, for the more aggregated scale levels, the 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 partly 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 (Fig. 1) may account for the strong positive contribution of the urban population in explaining the natural vegetation variance at more detailed scales.

Secondary vegetation

This poorly defined land use/cover class 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. The explaining variable altitude, and to a lesser extent the urban population, have negative relationships with secondary vegetation, whereas the remaining variable agricultural labour force displays a positive relationship. The contributions change only slightly with scale, whereas model fits remain poor.

Interpretation In both 1973 and 1984 most secondary vegetation is found at lower altitudes in rural areas 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 partly to 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 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) 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, whereas 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 centres.

Permanent crops

The variance in permanent crop distribution was modelled with relief, urban population and agricultural labour force as independent explaining variables displaying changing fits (30% to 75%) (Fig. 3). Maximum fits are found at 9 and 16 aggregated 0·1° grid 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, whereas 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). The positive contribution of agricultural labour force decreases at a less detailed (more aggregated) spatial scale whereas the urban population permanent crops relationship switches from strongly negative to a positive relationship 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 centres (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

Coffee areas are well modelled by altitude, relief (only 1984), soil drainage (only 1973), urban population and agricultural labour force (Fig. 4). Model fits range from 50% to 85%. Agricultural labour force and altitude have positive contributions whereas 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 centres 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
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. 4).

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) 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). 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 years modelled, 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 relatively 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 favourable conditions, whereas peasant household farms, producing for the regional and local markets, often have few alternative choices leading to sub-optimum production conditions (inputs) or to converting 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. 4).

Maize area
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, whereas 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
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, whereas 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 technically well optimized in the most suitable areas and probably mainly produced as a commercial crop.

Bean areas
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 centres. The similarity with the maize area model is obvious. Because both crops do not have such a clear biophysical optimization as rice, they are most probably grown both by large producers and by small holders.

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. 5) 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

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 to high coffee yields. Furthermore, higher yields are obtained in areas not too close to urban centres. In 1973, higher yields were found at relatively higher altitudes, whereas 1984 yields were higher at relatively lower altitudes. This difference suggests a climatic cause but may also be related by land degradation between 1973 and 1984 in coffee fields at higher altitudes, which corresponds to steeper slopes.

Banana yields

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 relatively large agricultural labour force and a relatively small rural population; a condition valid for the Atlantic Zone where most bananas are grown.

Maize yields

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 centres.

Rice yields

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 relationships 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 as such accounting for the changing contribution of urban population in the rice yield regression models.

Bean yields
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 centres may be explained by sub-optimum production conditions. Because the average farmer in Costa Rica strives for a financial optimization for his/her household (Kruseman *et al.*, 1994), a relatively large amount of time may be spent 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 centres could account for the relatively lower yields on non-commercial farms near urban centres. This interpretation suggests that higher commodity prices and lower urban wages would lead to an intensification of the smallholder farming in the peri-urban areas of Costa Rica. Similarly, the lower yields of the commercial crops coffee and rice near urban centres 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 & Hall (1993). The older agricultural areas which are generally thought to be found near the urban centres are considered as the most degraded ones, accounting for the lower yields. Most probably such a degradation effect cannot be excluded, but because severe land degradation is not only limited to peri-urban areas (Alfaro *et al.*, 1994 and Pollak & 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.

Changes in land cover

Finally, the changes in land use/cover distribution from 1973 to 1984 were modelled with multiple regression for the six spatial scales (Fig. 6). 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, which might be related to the non-linear characteristics of the modelled changes. Because we only have data for two different years we can only assume that the changes are linear. When data for 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 contribution of rural population and a less important positive association with altitude. An increase in permanent crops seems thus to be 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 good model fits (up to 93% at scale 6). Apart from the rural population, the growth in urban population seems to be related to an increase in coffee areas near the urban centres, but this increase mainly took 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 relationships 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 relationships 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 to be related to a decreasing agricultural labour force and an increasing urban population, and is found in relatively steeper areas on well-drained soils.

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 11 years. Demographic factors (urban and rural population growth) are the main drivers of land use *changes* as such, whereas 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 indicate that certain land use/covers, such as 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 centres 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 relationship 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, 1976*a*; DGEC, 1987*a*)) 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 (1994) on different evidence. This is also confirmed by the observation that cattle are also a status symbol and provide security for smallholders (Alfaro, personal communication, September 1994). This indicates that deforestation for pasture expansion in Costa Rica from 1973 to at least 1984 was not driven by land shortage caused by 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 centres 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 are usually 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, frequently 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 (Table 1). The prevalence of shifting cultivation and fallow systems favours extensive areas with regrowth of secondary vegetation. Again deforestation is not linked to land shortage or high population densities. Low input management and unfavourable biophysical conditions made arable lands of local farms less productive than the relatively well-managed and optimized commercial lands. This 'underuse' of local arable lands was also reported in a regional study of the Atlantic Zone (Alfaro *et al.*, 1994) where higher production potentials 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 & 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 population growth or migration, deforestation would have taken place between 1973 and 1984.

In summary, in Costa Rica we observed 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 favourable 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 subsidies on certain crops (Lutz & 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 past decade (Hall & 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 spatially 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' variables at higher aggregation scales, seems to have had no major effect on the regression results because most models have better model fits at more aggregated scales. It should be emphasized that this exclusion can, in cases with poor model fits, considerably hamper 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. Because it is virtually impossible to address all these scales it is something we have to live with. Second, 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 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 & 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.

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