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Evaluating impact of spatial scales on land use pattern analysis in Central America

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Abstract

The complexity of the relations between land use patterns and their spatial determinants causes the scale of analysis to influence the results. Often, focus is on one aspect of this scale effect, the spatial resolution. This study emphasises the influence of a varying spatial extent on the analysis of land use patterns in six countries in Central America. Statistical techniques are used to determine the relationship between six land uses and a number of potential determining factors, varying both resolution and extent. Results indicate that the effect of spatial resolution, by aggregating a basic grid to larger units, is small in comparison with other similar studies. The effect of a varying extent, by keeping either national boundaries or analysing the entire region at once, on the other hand, is substantial. An unrealistic redistribution of all major land use types, including a large-scale reforestation, is predicted using statistical analysis with the entire region as extent. When expanding the extent to a unit larger than a country, implicit assumptions concerning market mechanisms and national policies are adopted that do not correspond to the actual situation. Despite the existence of the Central American Common Market, it cannot be assumed that any agricultural land use will expand to satisfy an increasing demand in another country. Findings strongly suggest that any modelling effort at regional or global level should incorporate a thorough analysis of the effects of spatial scale on land use change predictions. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Land use; Spatial analysis; Scale; Central America; Scale of analysis

1. Introduction

1.1. Scale

It has been widely acknowledged in earth sciences that the scale of observation can influence the outcome of an analysis (Cocklin et al., 1997). A prime reason is the complex web of interactions and feedbacks formed by the underlying biophysical and socio-economic processes (Turner et al., 1995; Gibson et al., 2000). At more detailed scales, the non-linear nature of many relationships inhibits translation from one hierarchical level to higher or lower levels (Rastetter et al., 1992; Hijimans and Van Ittersum, 1996). In particular, landscape ecologists have made an effort to quantify the scale effect (O'Neill, 1988; Wiens, 1989; Levin, 1992), and the field of land use research is not lagging behind (Turner et al., 1995; Nunes and Augé, 1999). Following White and Running (1994), we define scale as "both the limit of resolution where a phenomena is discernible and the *extent* that the phenomena is characterised over space and time". Most studies, however, are limited to the effect of spatial resolution (see Gibson et al., 2000). The effect of changes in the spatial extent of the study area is probably the lesser-analysed dimension of the scale effect. Although extent and resolution are not completely independent for practical reasons, the

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effect on conclusions of an analysis can be different. A coarser resolution will reduce heterogeneity, while a larger extent will include more processes related to land use and land use change, and previously important processes may loose significance (King, 1991). Moreover, the same process might act at a different rate in different parts of the study area. The explaining factors of land use patterns will likewise change with changing resolution or extent. In this paper, we quantify the specific problems of both a changing spatial extent and spatial resolution of the analysis.

1.2. Spatial scale in land use modelling

Models that relate land use, and more specifically land use patterns, to its determining factors cover a broad range of spatial scales. At spatially detailed scales, the direct actors of land use change can be identified and process-based relationships can be determined. With decreasing resolution and increasing extent, it becomes increasingly harder to identify key *processes*. It is at these coarser levels that type of model and model assumptions have to change, as one can neither simply use nor extrapolate knowledge of local studies and employ it at another level. Yet, a large number of global change models exist (e.g. DICE (Nordhaus, 1992), PAGE (Hope et al., 1993), and IMAGE (Alcamo et al., 1998)), in which land use is usually incorporated. In IMAGE 2.1, e.g., the earth is subdivided into a number of world regions, assuming a generally similar history (Zuidema et al., 1994), without analysing the consequences of either the chosen spatial extent or resolution on resulting land use patterns. This study aims at an analysis of the feasibility of lumping together several countries into regions.

1.3. Study area

Central America (Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama) was selected as study area. It is an area with large historical, political, and sociological differences, but with ample similarities between the individual countries as well (Jones, 1988; Diaz-Bonilla, 1990). Civil wars (Nicaragua, El Salvador), economic instability after the second oil crisis (all countries), and population pressure (Guatemala, El Salvador) were important factors in the recent history of Central America. In recent years existing differences are gradually disappearing by a continuing process of market liberalisation and formation of common markets (Bulmer-Thomas, 1998). Past dissimilarities, however, continue to have differentiating influences on the six countries. Even so, the dominant land uses are the same in all countries (FAO, 1999). Three permanent crops, bananas (*Musa* spp.), coffee (*Coffea* spp.) and sugar cane (*Saccharum officinarum*), dominate the agricultural export. Pasture is by far the largest land use in terms of area and is used for both beef (lowland) and cow milk (mountains) production. A substantial part of the agricultural area is used to produce a variety of annual crops, most important being maize (*Zea mays*), beans (*Phaseolus* spp.), rice (*Oryza sativa*), and sorghum (*Sorghum* spp.). There is a shift from maize production in Guatemala and El Salvador to rice and bean cultivation in Costa Rica and Panama, related to a changing diet composition. A large part of most countries is still covered by some kind of natural vegetation, mostly forest. Extensive areas with tropical rainforest remain in Panama and Guatemala, and Honduras and Nicaragua share one of the largest continuous areas of forest in Latin America. El Salvador, on the other hand, is almost completely deforested.

1.4. Land use determining factors

Land use in Central America is influenced by a great variety of factors that act at different scales. In this paper, the analysis is restricted to the spatial determinants of land use patterns, and includes potential proximate causes of land use patterns. Underlying driving forces like (inter)national policies or infrastructure development are not considered. In view of the mostly volcanic mountain ranges that shape the appearance of most countries, altitude and thus rainfall, temperature and slope, are important determinants of land use patterns. Soil chemical and physical characteristics are another important group of factors that influence land use in the region. Besides those environmental constraints, demographic and other socioeconomic variables, like location of cities, population density, or level of education, are main spatial determinants of land use. However, the relatively coarse spatial resolutions that are addressed here could obscure processes that influence land use. Apparent relationships will sometimes represent proxies of processes that are visible at the farm level. Population density, for instance, is often established as land use determinant, but is normally an indirect indicator of labour availability, accessibility, or presence of local markets. We therefore necessarily opted for an empirical, data-driven rather than a knowledge-based approach.

1.5. Research framework

This study is part of a series of research activities related to a land use change model, the CLUE (conversion of land use and its effects; Veldkamp and Fresco, 1996; Schoorl et al., 1997) modelling framework. CLUE can be described as a dynamic, multi-scale land use change model, which explores the spatially explicit effects of future land use changes, using scenarios. Land use allocation is the subject of one of the key modules; scenarios are constructed at national level in the demand module. For details about the modelling framework and modelling sequence, De Koning et al. (1999) provide good background using data from Ecuador. The allocation module is described in detail by Verburg et al. (1999a). In the context of this paper it suffices to know that for every application of the model, multiple regression equations at multiple resolutions as described here are generated. Those equations are subsequently used in the allocation module. Previous research concerning the spatial determinants of land use at different spatial scales include the Atlantic Zone of Costa Rica (Kok and Veldkamp, 2000), Costa Rica (Veldkamp and Fresco, 1997), Ecuador (De Koning et al., 1998), Java (Verburg et al., 1999b), and China (Verburg and Chen, 2000). All focused primarily on the effects of spatial resolution. The effects of a varying extent have been touched upon (Verburg and Chen, 2000), but it always concerned a separation into different (agroecological) zones within one country. The effect of grouping different countries has not been investigated before. The results of the statistical analysis presented in this paper will be used for the application of the CLUE modelling framework to Central America (CLUE-CA; Kok and Winograd, 2002). Consequently, part of the methodologies employed, such as the type of statistical analysis, the basic resolution, and the number of land use types included, are predefined by model requirements of the allocation module.

1.6. Objectives

The objectives of this study are to

1. quantify relationships between the distribution of land use and a set of potential demographic and biophysical explaining factors at the regional level;
2. specifically analyse both aspects of spatial scale, by varying resolution and extent;
3. analyse the effects of different extents on the input of the CLUE allocation module.

2. Methods and materials

2.1. Data format

Data format is in accordance with the data needs of the CLUE-CA allocation module. A grid-based approach is followed with a pixel size of $15 \times 15\,\mathrm{km}^2$ as basic unit for analysis. Pixel size is based on the average size of the input units, as well as on the pixel size of other applications of CLUE in the region. Thus, a direct comparison is enabled with studies of the Atlantic Zone of Costa Rica (Kok and Veldkamp, 2000), and Honduras (Kok, 2001). Instead of using uniform gridcells with one dominant land use type and one average or dominant value for every explaining variable, sub-grid information is present for most of the spatial determinants and each land use type. In every cell, we use, e.g. the percentage of highly fertile soils and the percentage of each land use. In this way, we do not lose any information when either gridding the data or scaling up, although spatial precision decreased.

2.2. Dependent variable: land use

The data of an agricultural census, the main data source within the CLUE framework, can be described best as ‘land cover with aspects of land use’. In this paper, the term land use rather than land cover is adopted to refer to the above class description, although, e.g. the class natural vegetation is more closely related to a cover. A land use map is obtained by combining data from two, basically different, sources: agricultural census data and existing land use maps. Agricultural censuses contain a wealth of information

Table 1
Date of most recent agricultural census and most recent land use map available for every country. Number of administrative units indicate the number of third level units (usually counties)

Country	Year of most recent agricultural census	No. of administrative units	Most recent land use map
Costa Rica	1984	82	Forest map, 1996
El Salvador	Not available	263	Land use, 1993
Guatemala	1979	329	Forest map, 1992
Honduras	1993	292	Forest map, 1995
Nicaragua	1995, department level	144	Land use, 1992
Panama	1990	68	Not available

on a large number of annual and perennial crops. Because of this thematic detail, census data are used as main source of information. Existing land use maps, containing normally not more than a few broad classes, are used to update the census data, or to increase the spatial detail of the map. For Panama and Honduras no land use map is used, as recent, thematically and spatially detailed, census data is available. For El Salvador (not available) and Guatemala (outdated), the agricultural census is omitted. Table 1 summarises the employed information for the countries involved. Information is extracted from an existing database (CIAT, 2000), that was made available. In Fig. 1, the spatial distribution of administrative units is visualised. Resulting national land use maps are subsequently updated to 1996, using temporally detailed, national statistics (FAO, 1999) on area development of all land uses since the most recent census. This polygon map is finally rasterised at various resolutions.

Every gridcell of the final map contains percentage information on six land use classes, which encompass the most important uses in terms of area and economic profit: (1) annuals (mainly rice, maize, beans, and sorghum); (2) bananas (including plantains (*Musa*

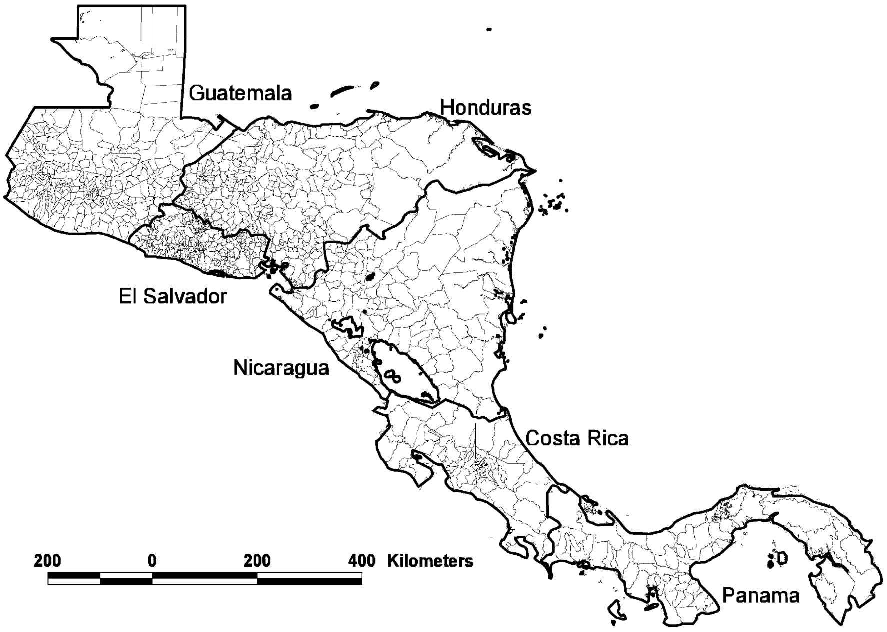


Fig. 1. Location of six Central American countries included in analysis. Thick lines indicate country boundaries. Thin lines represent third level administrative boundaries.

Table 2
Relative area coverage (% of total area) of the most important land use types in individual countries and entire region (Central America) in 1996

Spatial extent	Annuals	Bananas	Coffee	Sugar cane	Pasture	Natural vegetation
Costa Rica	6	1	2	1	29	61
El Salvador	19	<1	11	2	46	21
Guatemala	16	<1	3	1	32	49
Honduras	6	<1	2	<1	14	78
Nicaragua	9	<1	<1	1	20	70
Panama	7	<1	<1	<1	21	71
Central America	9	<1	2	1	24	64

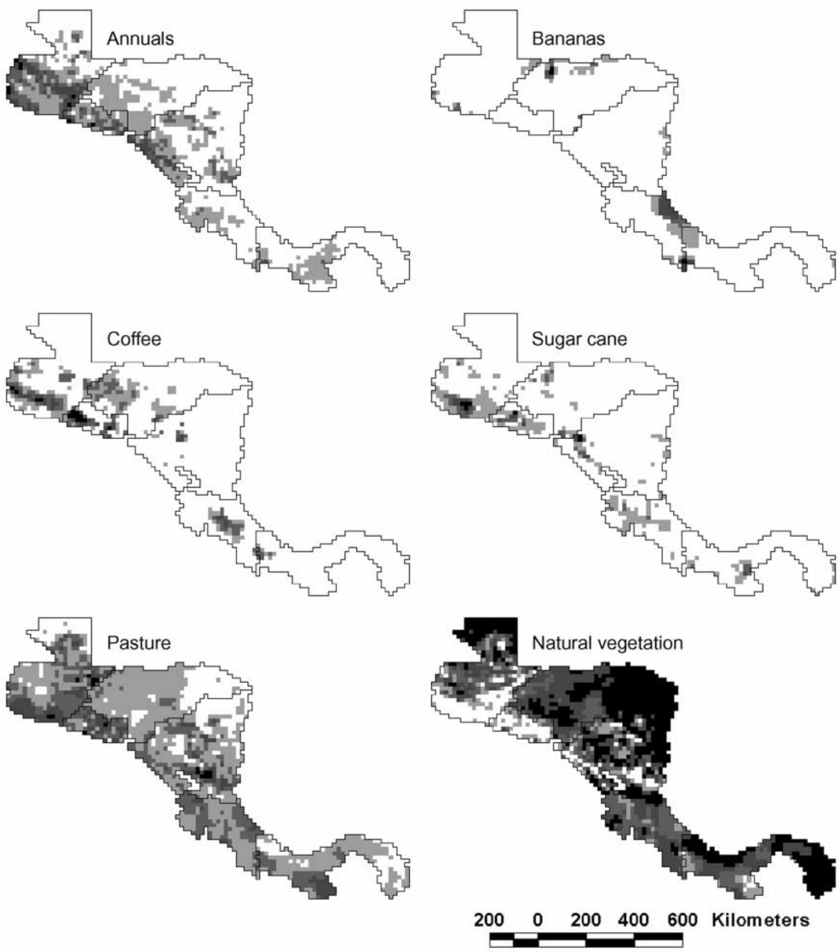


Fig. 2. Land use patterns in 1996. Light colours indicate a low cover percentage; dark colours a high cover percentage.

paradisiaca)); (3) coffee; (4) sugar cane; (5) pasture (excluding natural pastures); (6) natural vegetation. This last group mainly consists of tropical forest, but also includes, e.g. secondary regrowth, natural pastures, and built-up area. Urban area covers maximally 5% of any country and is therefore not treated as a separate land use type. In Table 2, the relative area coverage of all land use types is given at national level; Fig. 2 visualises land use patterns in 1996.

2.3. Independent variables

From the enormous variety of possible spatial determinants of land use, a pre-selection is made. Table 3 lists the limited but broad selection of possible determinants that are used in the statistical analysis. Grouping of categorical variables like FERTHIGH and FERTLOW reduces the number from 22 to 16, labelled as ‘groups’ in Table 3. All information is extracted

Table 3
Basic information of variables included in the multiple regression analysis

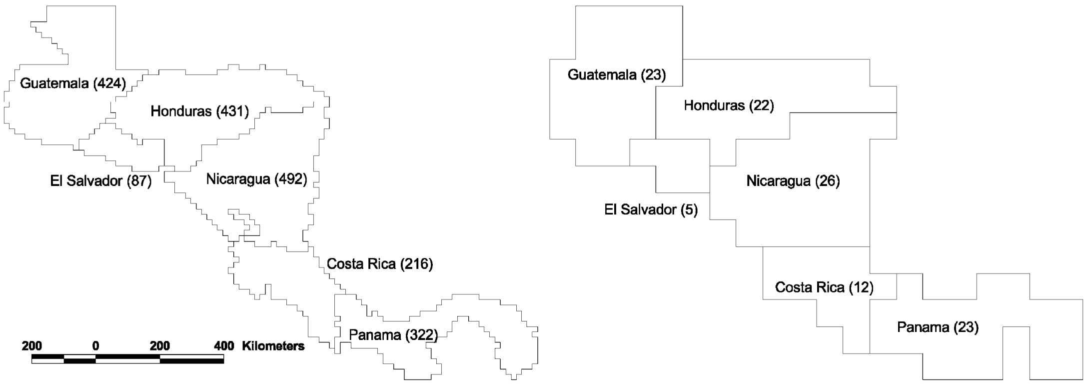
Variable	Explanation	Unit	Source
Demographic (five variables; five groups)			
DENRUR	Rural population density	Individuals/ha	Population censuses of various years
DENURB	Urban population density	Individuals/ha	
PERRUR	Fraction of population classified rural	% of population	
ACCPORT	Access to nearest port; measured as weighted distance to nearest port	m	Accessibility map, CIAT, Colombia
ACCMARK	Access to nearest market; measured as weighted distance to nearest market	m	
Soil (10 variables; five groups)			
DEPSHAL	Shallow soils: normally <50 cm	% of gridcell	FAO soil map of the world
DEPDEEP	Deep soils: >120 cm	% of gridcell	
DRAIBAD	Poorly drained: water stagnation during a substantial part of the year	% of gridcell	
DRAIGOOD	Well drained: no water stagnation	% of gridcell	
FERTHIGH	High fertility: high yields, suitable	% of gridcell	
FERTLOW	Low fertility: low yields, not suitable	% of gridcell	
PHHIGH	pH > 6	% of gridcell	
PHLOW	pH normally lower than 4.5	% of gridcell	
TEXTCLAY	Topsoil with clayey texture	% of gridcell	
TEXTSAND	Topsoil with sandy texture	% of gridcell	
Other biogeophysical (five variables; four groups)			
SLOPFLAT	Flat terrain: slope <1%	% of gridcell	Digital Elevation Model
SLOPSTEEP	Steep slopes: slope >5%	% of gridcell	
ALT	Altitude	m	
RAINTOT	Average annual total precipitation	mm	Monthly rainfall maps, CIAT, Colombia
DRYMONTH	Consecutive months with <60 mm precipitation	Number	
Park presence (two variables; two groups)			
PARKALL	Area within any type of protected area	% of gridcell	Map with parks and description, CIAT, Colombia
PARKNAT	Area within national park	% of gridcell	
Omitted variables			
DENTOT	Total population density	Individuals/ha	Population censuses
DISTROAD	Distance to nearest road	m	Topographic map, CIAT, Colombia
DEPMED	Medium soil depth: normally 50–120 cm	% of gridcell	FAO soil map of the world
DRAINMED	Moderately drained: some water stagnation	% of gridcell	
FERTMED	Medium fertility: moderate yields	% of gridcell	
PHMED	pH between 4.5 and 6	% of gridcell	
TEXTMED	Topsoil with silty texture	% of gridcell	
SLOPMED	Moderate slopes: 1–5% slope	% of gridcell	Digital Elevation Model

from an existing database (CIAT, 2000). Explaining factors are divided into four functional groups to facilitate interpretation.

- Demographic factors include population density (rural and urban), percentage of rural population, and two measures of accessibility. Population density is a dynamic variable and, much like for land use, a 1996 map needed to be constructed from various national sources. For every country at least two population censuses are available, of which the most recent was invariably conducted in the 1990s. National growth rates (FAO, 1999) of subsequent years are combined with spatial explicit growth rates derived from the two censuses to obtain a 1996 population map for the entire region.
- Soil variables include information on soil fertility, pH, drainage, depth, and texture of topsoil.
- Other biogeophysical factors include altitude, precipitation, number of consecutive dry months, and slope steepness.
- The only factor related to land use policies, for which consistent spatially explicit information was available for all countries, was the location of national parks and other protected areas.

2.4. Spatial scales

Previous research within the CLUE framework on the effect of an decreasing resolution has indicated that the highest explaining power of multiple regression equations is obtained using a grid that is 9–36 times larger than the basic resolution. Based on this information, a second aggregation level of $75 \times 75\,\mathrm{km}^2$ is selected, an aggregation of 5×5 cells of the basic level. The analysis is thus restricted to two aggregation levels, the minimum input of the CLUE allocation module. A third, intermediate, resolution of $45 \times 45\,\mathrm{km}^2$ was initially included, but results varied little from the $75 \times 75\,\mathrm{km}^2$ resolution. To vary the extent, the statistical analysis is executed for the entire region as a whole and for every country separately. Grouping countries together implies that the region is treated as one organisational unit, with, e.g. one completely open market. The underlying assumption of the country extent is that differences in national policies and biogeophysical circumstances are such that land use distribution should be analysed at country level. At the coarse resolution, the analysis of Costa Rica includes the cells of Panama and El Salvador is analysed including Guatemala, as the number of data points is insufficient for separate analysis. Consequently,



Detailed spatial resolution (1972 data points) **Coarse spatial resolution (111 data points)**

Fig. 3. Spatial resolution of input data. Left side: $15 \times 15\,\mathrm{km}^2$ resolution; right side: $75 \times 75\,\mathrm{km}^2$ resolution. Numbers within brackets indicate the number of gridcells.

comparison between resolutions is difficult for Costa Rica and El Salvador. In Fig. 3, resolutions are visualised for all countries.

Before executing the multiple regression analysis, a couple of steps are taken to minimise the correlation between variables (multi-collinearity effects) and between neighbouring gridcells within one variable (spatial autocorrelation).

2.5. Multi-collinearity

Independency between variables is a prerequisite of the statistical method employed and several measures were taken to reduce the effects of multi-collinearity as much as possible. Of all classified variables (e.g. soil fertility) one categorical sub-class (e.g. percentage of medium fertile soils) is omitted from the analysis for reasons of data redundancy. Subsequently, of all pairs of variables with a correlation over 0.80, one is omitted from the analysis. Of all pairs of variables with a correlation over 0.50, only one is allowed to enter a regression equation. The use of a stepwise regression procedure solves remaining multi-collinearity problems. Omitted variables are listed in Table 3. Pairs of correlated variables (>0.50) are number of dry months and total precipitation (DRYMONTH and RAINTOT); percentage of population classified rural and rural population density (PERRUR and DENRUR); presence of national park and presence of any type of protected area (PARKNAT and PARKALL); high soil pH and high soil fertility (PHHIGH and FERTHIGH); altitude and steep slopes (ALT and SLOPSTEEP).

2.6. Spatial autocorrelation

Spatial autocorrelation can obscure the results of a regression analysis (Anselin and Griffith, 1988; Chou, 1991). The regression coefficient and significance of the contribution of individual variables are sensitive for the presence of autocorrelation. Unfortunately, with this alternative manner to calculate multiple regression equations it would be far too time consuming to use a stepwise procedure, especially considering the high number of equations that need to be calculated. Consequently, either a theoretical combination of explaining variables has to be available in advance, or methods that correct for autocorrelation have to be abandoned. Alternatively, a check on the presence of spatial autocorrelation in the residuals of a regression equation can be performed. Overmars (2000) analysed the influence of spatial autocorrelation using a multi-resolution dataset from Ecuador, over a range of resolutions similar to this study. Results indicated the presence of spatial autocorrelation at the most detailed resolution ($9.5 \times 9.5\,\text{km}^2$) and a rapid decrease at coarser resolutions. Moreover, most multiple regression equations varied little when a spatial autoregressive model was used. The three most important spatial determinants were identical in most cases. We therefore opt to ‘disregard’ the effects of spatial autocorrelation and limit the interpretation of the equations to the three most important variables in terms of standardised betas.

2.7. Statistical analysis

The relationships between land use and the selected set of variables are quantified in a two-step procedure, using multiple regression techniques. First, significantly contributing variables are selected with a stepwise regression procedure, using the 0.05 significance criterion. Subsequently, this set of variables is used to construct multiple regression equations. The procedure is repeated for every land use type, for both resolutions, and for the various extents. The adjusted coefficient of determination (R^2) serves as a measure for the amount of variation explained. The standardised regression coefficients (standardised betas or β_{st}) are used to indicate the relative importance of individual variables in a given equation.

When multiple regression equations are applied, the results can be used as a prediction of the cell-specific land use distribution. This so-called ‘regression cover’ is a key input in the CLUE allocation module. The effect of a changing extent on the resulting regression covers is analysed.

3. Results

3.1. Coefficient of determination

In Table 4, adjusted coefficients of determination (R^2) are given for 84 statistical models. The average of the six national analyses is weighted by country size, the average for land use by total area. With the

Table 4
Adjusted coefficients of determination ($\bar{R}^2$) of all multiple regression equations (CAM: Central America; GUA: Guatemala; ELS: El Salvador; NIC: Nicaragua; HON: Honduras; COS: Costa Rica; PAN: Panama)

Land use type	CAM	GUA	ELS[a]	NIC	HON	COS[b]	PAN	Average countries[c]
Fine resolution								
Annuals	*0.28*	0.47	0.48	0.36	0.79	0.30	0.53	*0.51*
Bananas	*0.15*	0.18	0.12	0.14	0.49	0.50	0.23	*0.28*
Coffee	*0.25*	0.42	0.43	0.18	0.39	0.76	0.42	*0.39*
Sugar cane	*0.11*	0.25	0.17	0.12	0.24	0.26	0.17	*0.20*
Pasture	*0.28*	0.58	0.35	0.23	0.59	0.23	0.60	*0.45*
Natural vegetation	*0.40*	0.69	0.32	0.27	0.74	0.33	0.63	*0.53*
Coarse resolution								
Annuals	*0.49*	0.91	0.85	0.78	0.94	0.56	0.87	*0.84*
Bananas	*0.32*	0.80	0.36	0.83	0.86	0.50	0.83	*0.78*
Coffee	*0.81*	0.83	0.27	0.76	0.77	0.86	0.86	*0.78*
Sugar cane	*0.25*	0.40	0.41	0.68	0.61	0.30	Not significant	*0.45*
Pasture	*0.57*	0.91	0.90	0.89	0.90	0.55	0.82	*0.85*
Natural vegetation	*0.65*	0.94	0.95	0.83	0.96	0.73	0.85	*0.88*

[a] At the coarse resolution, the analysis of El Salvador included the cells of both Ecuador and Guatemala.

[b] At the coarse resolution, the analysis of Costa Rica included the cells of both Costa Rica and Panama.

[c] Weighted by country size.

exception of sugar cane in Panama at the coarse resolution, a statistically significant model is always established. Coefficients of determination vary between 0.11, for the explanation of the distribution of sugar cane in the whole region at the fine resolution, and 0.96, for the distribution of natural vegetation in Honduras at the coarse resolution. In the majority of the cases, the R^2 is satisfactory, but large differences exist between land use type, extent, and resolution.

The distributions of land use types that cover large areas (annuals, pasture, and natural vegetation, see Table 2) are explained best. The R^2 of annuals (weighted average 0.51 at detailed resolution), pasture (0.45) and natural vegetation (0.53) are relatively high. At the coarse resolution, differences with the three permanent land uses are less pronounced, but present. The distribution of sugar cane is poorly described by the set of potential spatial determinants. Part of the explanation for the difficulties in explaining the distribution of low covering land uses is found in the high number of cells that have a very low cover (0–5%), but with a high variation. Location of large plantations is normally correctly predicted, but the variability in the low range is hard to capture with linear regression methods.

The R^2 increases substantially when the extent is reduced from regional to national. Comparing the model performance of regional and average country analyses (italic numbers in Table 4) at the detailed resolution, an increase between 0.09 (sugar cane) and 0.23 (annuals) is obtained using country extent. At the coarse resolution, the increase is about twice that amount. The same applies for the analyses of most individual countries at both resolutions and for all land uses. Exceptions are the poor explanation of banana distribution in El Salvador, which relates to the extremely low area covered by bananas (about 1 km^2), and the generally poor results for Nicaragua at the detailed resolution, which can probably be attributed to poor data quality. The consistently lower explanatory power at the supra-national level demonstrates the importance of underlying driving forces, which are more difficult to quantify. Differences in national policies, history, and tradition account for, e.g. large areas of coffee in El Salvador, though only 5% of the country is suitable, while 30% of the neighbouring Guatemala (3.5 million hectares) could be used for coffee plantations but is not.

All models have a higher explanatory power at the coarse than at the detailed resolution. In general, the R^2 roughly doubles when using a 25-fold larger resolution. Equations of the most important land uses in terms of area have coefficients of determination at the coarse resolution generally above 0.80 as opposed to about 0.50 at the detailed resolution. The increase of

Table 5
Three most important explaining factors in terms of standardised beta for all multiple regression equations. Variables are listed in order of importance (CAM: Central America; GUA: Guatemala; ELS: El Salvador; NIC: Nicaragua; HON: Honduras; COS: Costa Rica; PAN: Panama)

Land use type	CAM	GUA	ELS[a]	NIC	HON	COS[b]	PAN
Fine resolution							
Annuals	DRYMONTH+ DENRUR+ PHHIGH+	DRYMONTH+ ACCPORT− PERRUR+	ALTITUDE+ ACCMARK− SLOPSTEEP+	ACCPORT− DEPSHAL+ FERTHIGH+	DENRUR+ ACCPORT− DRYMONTH+	DRYMONTH+ FERTLOW+ DRAIGOOD+	ACCPORT− DRYMONTH+ FERTHIGH+
Bananas	DRYMONTH− ACCPORT− TEXTSAND+	ACCPORT− SLOPFLAT+ DRAIGOOD−	PERRUR+ RAINTOT− DRAIGOOD+	PARKALL− ACCPORT+ RAINTOT+	DENRUR+ DRAIGOOD− DRYMONTH −	DRYMONTH− DEPDEEP+ FERTHIGH−	DENRUR+ FERTHIGH+ PHLOW−
Coffee	TEXTSAND+ DRYMONTH+ DENRUR+	SLOPSTEEP+ DRYMONTH+ FERTHIGH+	ALTITUDE+ ACCPORT− DRAIBAD+	ALTITUDE+ DENRUR+ DRYMONTH−	DENRUR+ FERTLOW− ALTITUDE+	DENRUR+ DRAIGOOD− ALTITUDE+	ALTITUDE+ TEXTSAND+ DENRUR+
Sugar cane	PHHIGH+ RAINTOT+ ACCPORT−	DRYMONTH+ DENRUR− ACCPORT−	FERTHIGH+ TEXTSAND+ DRYMONTH−	PHHIGH+ ACCMARK− RAINTOT+	DENRUR+ PHHIGH+ DRAIGOOD−	PHHIGH+ DENURB− DRYMONTH+	DRYMONTH+ FERTHIGH+ DRAIBAD−
Pasture	ACCPORT− PHHIGH+ DRAIBAD+	ALTITUDE− ACCPORT− PARKALL−	SLOPFLAT− ACCPORT+ DEPDEEP−	ACCPORT− DEPSHAL+ SLOPFLAT−	DENRUR+ FERTHIGH− RAINTOT−	PHLOW− ACCPORT− DRAIGOOD+	ACCMARK− DRYMONTH+ DEPSHAL+
Natural vegetation	ACCPORT+ PHLOW+ RAINTOT−	ACCPORT+ ALTITUDE+ DRYMONTH−	FERTHIGH− ACCMARK+ DRYMONTH−	ACCPORT+ PERRUR+ DEPSHAL−	DENRUR− DRAIBAD− PHHIGH−	PHLOW+ ALTITUDE− ACCPORT+	DRYMONTH− ACCMARK+ FERTHIGH−
Coarse resolution							
Annuals	DRYMONTH+ ALTITUDE+ FERTHIGH+	SLOPSTEEP+ DENRUR− FERTLOW−	SLOPSTEEP+ DENRUR− FERTLOW−	ACCPORT− ALTITUDE− DEPDEEP+	DENRUR+ DRYMONTH+ ACCPORT−	DRYMONTH+ DEPDEEP− ACCPORT−	DRYMONTH+ SLOPSTEEP+ ACCPORT−
Bananas	DRYMONTH− ACCPORT− TEXTCLAY−	SLOPFLAT+ ACCMARK− FERTHIGH−	ACCPORT− SLOPFLAT+ DRYMONTH−	DEPDEEP+ PERRUR+ PHLOW−	DENURB+ DRYMONTH+ TEXTCLAY−	TEXTCLAY− RAINTOT+ PHLOW−	FERTHIGH+ DRYMONTH+ DEPDEEP+
Coffee	DENRUR+ ALTITUDE+ DEPDEEP+	DRAIGOOD+ DEPDEEP+ ALTITUDE+	DENRUR+ DEPDEEP+ ALTITUDE+	ALTITUDE+ DENRUR+ ACCPORT+	FERTLOW− DENRUR+ DEPDEEP−	DENRUR+ ALTITUDE+ SLOPSTEEP+	ALTITUDE+ FERTHIGH+ DENRUR+
Sugar cane	PHHIGH+ ACCPORT− SLOPFLAT+	DEPSHAL− PHLOW− DRAIBAD−	DRAIBAD− DEPSHAL− RAINTOT+	PHHIGH+ ACCMARK− DENRUR−	DENRUR+ DEPSHAL− Not significant	FERTHIGH+ DRYMONTH+ DENURB−	No significant model
Pasture	PHHIGH+ DRYMONTH+ DRAIBAD+	DEPDEEP+ ALTITUDE− PARKALL−	DEPDEEP+ ALTITUDE− PARKALL−	ACCPORT− ACCMARK+ DEPDEEP+	DENRUR+ DRYMONTH− ACCPORT+	ACCMARK− DRYMONTH+ DRAIBAD+	DEPDEEP− ACCMARK− PERRUR−
Natural vegetation	PHHIGH− ACCPORT+ DRYMONTH−	SLOPSTEEP− DEPDEEP− PARKALL+	DEPDEEP− SLOPSTEEP− PARKALL+	ACCPORT+ FERTHIGH+ ALTITUDE+	DENRUR− DRYMONTH+ PHLOW+	FERTLOW− DRYMONTH− DENURB+	DRYMONTH− DEPDEEP+ ACCMARK+

[a] At the coarse resolution, the analysis of El Salvador included the cells of both Ecuador and Guatemala.

[b] At the coarse resolution, the analysis of Costa Rica included the cells of both Costa Rica and Panama.

explanatory power of models for the three permanent crops is generally less. Because the analysis uses only two resolutions, conclusions on the effect of resolution are limited.

3.2. Variable importance

In Table 5, the three most important variables in terms of β_{st} of all equations are listed. None of the equations include more than 10 variables and the variables listed in Table 5 generally account for at least 75% of the total explaining power. Table 6 is a quantification of Table 5, by counting the number of occurrences of (groups of) variables, both for the entire region and for the six individual countries. All groups of variables, except park presence, contribute substantially to the explanation of the distribution of land use. A remarkable small range of 22% (demography at coarse level) to 40% (soil at coarse level) is found in the relative importance of demographic, soil, and other biogeophysical variables in the regression equations (Table 6).

There are no apparent effects of changing resolution on the importance of the three variable groups (Table 6). Examining the composition within the groups, however, reveals interesting shifts. When scaling up, soil depth (DEPDEEP) becomes more important and soil fertility (mostly FERTHIGH) loses importance. It could indicate that farmers generally prefer areas with deep soils, and look for the most fertile soils within those areas. A second change is the lower participation of climate seasonality (DRYMONTH) at the coarse resolution. This seems in contradiction with the intuitive tendency to perceive climate variables as being more important at coarser resolutions, and spatial changes in DRYMONTH and precipitation (RAINTOT) are indeed gradual. Most likely, it is the increasing importance of other variables that causes the decreasing participation of this climatic variable.

When analysing the results at the highly aggregated level of four variables groups, the effect of changes in extent is marginal as well. At the coarse resolution the effect is somewhat larger, considering the difference

Table 6
Variable importance in multiple regression models. Numbers are a count (No.) and percentage (%) of the three most important variables. 'CAM' represents the model run for the entire region; in the column 'countries', six national analyses are grouped

Variable group	Fine resolution				Coarse resolution			
	CAM (No.)	Countries (No.)	CAM (%)	Countries (%)	CAM (No.)	Countries (No.)	CAM (%)	Countries (%)
PERRUR/DENRUR	2	14	11	13	1	13	6	13
DENURB	–	1	–	<1	–	4	–	4
ACCMARK	–	5	–	5	–	5	–	5
ACCPORT	4	15	22	14	3	10	16	10
Population	6	35	33	32	4	32	22	32
DEPSHAL/DEPDEEP	–	5	–	5	1	17	6	16
FERTLOW/FERTHIGH and PHLOW/PHHIGH	4	19	22	18	4	14	22	13
DRAIBAD/DRAIGOOD	1	10	6	9	1	3	6	3
TEXTCLAY/TEXTSAND	2	2	11	2	1	3	6	3
Soil	7	36	39	34	7	37	40	35
ALT	–	9	–	8	2	9	11	9
RAINTOT/DRYMONTH	5	21	28	19	4	14	22	13
SLOPSTEEP/SLOPFLAT	–	5	–	5	1	8	6	7
Climate	5	35	28	32	7	31	39	29
PARKNAT/PARKALL	–	2	–	2	–	4	–	4
Park	0	2	0	2	0	4	0	4
Total	18	108	100	100	18	104	~100	100

between the contribution of soil (22 and 32% for the regional and national analyses, respectively) and other biogeophysical (39 and 29%) variables. However, substantial differences surface when examining the importance of single variables. A good example is the relation between altitude and coffee at the fine resolution: In the national analyses, altitude (ALT) or the related steep slopes (SLOPSTEEP) are always amongst the three most explaining variables, and in three countries (El Salvador, Nicaragua, and Panama) altitude is the most important one. Analysis at the regional extent fails to recognise altitude as important determinant of the location of coffee, and selects sandy soils (TEXTSAND) and rural population density (DENRUR) instead.

In all countries, annuals are cultivated preferably in areas with a pronounced dry period (Table 5, high importance DRYMONTH+), which is consistent with the reported need of annual crops for a dry period to complete ripening of the grain (Schelhas, 1996). The unimportance of access to nearest port (ACCPORT) in explaining the distribution of bananas seems remarkable. However, although banana plantations are never located far from a port (Hallam, 1995), not all ports have nearby banana plantations, which weakens the relationship. Coffee is typically cultivated above 1000 m, which is reflected by the presence of altitude, as well as correlated variables rural population density and steep slopes in the equations. The distribution of sugar cane is strongly related to indicators of good soils (positive correlation with high pH, high fertility, or deep soils), which also reflects the preference for locations close to water. Determinants of the distribution of pasture are often associated with low quality soils (positive correlation with poorly drained soils, low pH, or shallow soils), indicating that grassland is found at places unsuitable for other, more profitable, crops. The distribution of natural vegetation depends on a number of variables. Most important are associated with poor soils (low pH, low fertility) or demography (low rural population density, large distance to ports). Various variables that explain the distribution of natural vegetation have a counterintuitive sign (e.g. FERTLOW− in Costa Rica, and SLOPSTEEP− in Guatemala). The most likely cause is the diverse nature of the natural vegetation class. Furthermore, the overwhelming influence of rural population density in Honduras is noteworthy. Solely the variable rural population density explains about 50% of the variation in annual cover at the fine resolution and almost 80% at the coarse resolution, and it is the variable with the highest explanatory power in almost every equation. A separate study for the importance of population density in Honduras is forthcoming (Kok, 2001).

3.3. Spatial considerations

In Table 7, the relative area of three land use types as predicted by the regression equations is given, aggregated to country level. When aggregating a regression cover to the level at which the regression analysis is carried out, by definition the input situation (in this case, the actual land use in 1996) is approximated. Consequently, the aggregated cover percentage of an analysis at country level equals the actual situation in 1996 (see Table 2). When aggregating to a less coarse level, like the summation of the supra-national

Table 7
Relative area coverage (% of total area) of most important land use types as predicted by multiple regression equations for entire region (Central America) and for individual countries (countries). Bold (countries<) and italic (countries>) numbers show most conspicuous differences. Note that the regression cover for the analyses at national level equals the average actual cover of 1996 (see Table 2)

Country	Annuals		Pasture		Natural vegetation	
	Central America	Countries	Central America	Countries	Central America	Countries
Costa Rica	10	6	31	29	*52*	*61*
El Salvador	21	19	*38*	*46*	**31**	**21**
Guatemala	*10*	*16*	*23*	*32*	**64**	**49**
Honduras	9	6	**21**	**14**	*68*	*78*
Nicaragua	8	9	22	20	68	70
Panama	7	7	22	21	70	71

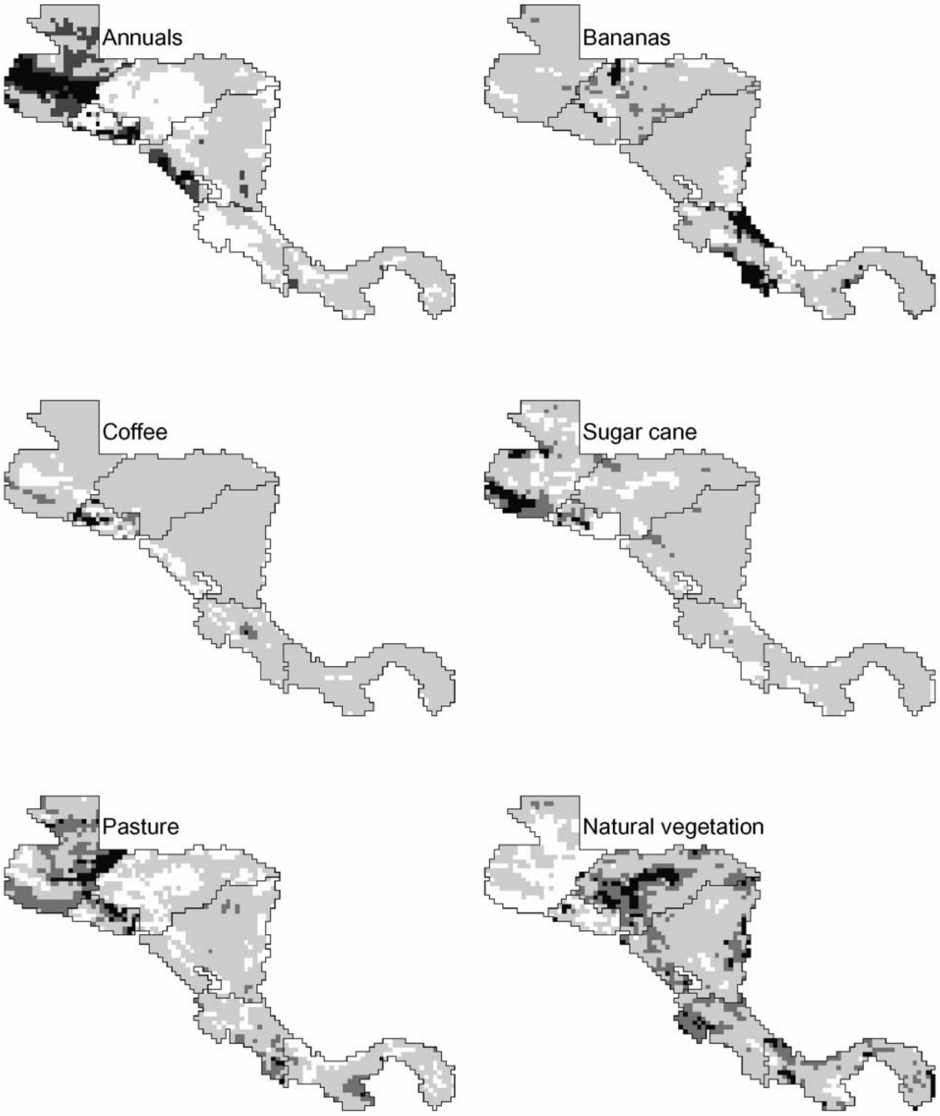


Fig. 4. Differences between cover percentage based on regional and national multiple regression equations. (Very) dark areas indicate places where a (much) higher cover percentage is projected by the national analyses; light shaded areas indicate a higher percentage in the regional analysis. Medium grey tones indicate similar percentages.

analysis to country level, the actual situation is not necessarily approached. Increasing the extent from national to regional provokes substantial changes all countries except Panama and Nicaragua. The regional analysis predicts large-scale redistributions of annuals, pasture, and consequently natural vegetation. A 10–15% reduction of the agricultural land (mainly pasture) could occur in Guatemala and El Salvador, countries where population pressure has historically been high and forest is scarce. This area (about 300,000 ha) could be taken into production in Costa Rica and Honduras. When the statistical models would be used to predict land use changes, a strong reforestation in Guatemala and El Salvador could take place, coupled with an accelerated deforestation in Honduras and Costa Rica.

Fig. 4 visualises the difference between the regression covers based on the regional analysis and the regression covers as calculated by using the national regression equations. Dark areas indicate places where a higher cover percentage is projected by the national analyses; the light areas indicate a higher percentage in the regional analysis. Apart from aforementioned examples, which are stressed again, the regional analysis predicts a shift of banana plantations from Costa Rica and Honduras (dark areas) to Panama and Nicaragua (white areas). When applying the regional instead of national regression equations, the recurrent pattern is a decreasing area of any agricultural land use of which the total cover percentage is relatively high. This decrease is accompanied by an increase in countries with abundant forested areas that are suitable for that land use type. An interesting detail is an area in the southwest of Costa Rica that is predicted to be deforested (dark grey areas) in the regional analysis, as it is the same area that has been reforested between 1975 and 1985, a period of large-scale population out-migration (Edelman, 1992).

4. Discussion

The overall results of the multiple regression analysis are satisfactory. Generally, coefficients of determination are (very) high, although at the fine resolution some equations yield a relatively low coefficient. Moreover, most of the spatial determinants included in the equations have the expected sign. This performance strongly suggests that for most land uses, the set of explanatory variables used includes the most important spatial determinants of land use in Central America. Soil, biogeophysical, and demographic factors are equally important in the explanation of land use patterns, and need to be included in any analysis of the distribution of land use at the (supra)-national scale. Rural population density, rainfall seasonality, and soil fertility are of highest importance.

Changing the spatial resolution from 15 × 15 to $75 \times 75\,\mathrm{km}^2$ in Central America does not greatly influence the analysis. Land use patterns are described by approximately the same set of spatial determinants. Findings contradict conclusions drawn by De Koning et al. (1998) for Ecuador, using a resolution range from 9×9 to $55 \times 55\,\mathrm{km}^2$, and Verburg et al. (1999b) for Java, with a range from 20×20 to $40 \times 40\,\mathrm{km}^2$, who employed the same methodology. Both studies indicate significant changes in variable composition and standardised betas with changing resolution. In the light of the previous work, the effect of resolution found here is remarkably small. The stability could be attributable to the coarse basic resolution relative to the total area, which may inhibit detection of scale-dependent relations at finer resolutions.

The effect of changing the extent is substantial. A redistribution of land uses is predicted to take place when using the supra-national extent. Countries with a relatively low pressure on the land will be deforested more rapidly, while in countries with a high agricultural output reforestation will take place. When analysing at the supra-national extent, the key underlying assumption becomes that the agricultural markets are completely open and products can be freely redistributed. A free market would boost import and export quantities in all countries and would thus facilitate, e.g. cultivation of annuals in Costa Rica to meet the domestic demand in Guatemala. This hypothetical situation that is implicitly assumed, is far from realistic. Although trade within the Central American Common Market has grown recently, it remains highly concentrated with exchanges between El Salvador and Guatemala (Bulmer-Thomas, 1998). Average intraregional trade of beef can be as high as 20%, but trade of annuals is normally less than 5% of the total production (Rueda-Juquera, 1998). As long as a large federation of states is not established and as long as agricultural land use remains based on subsistence farming in some countries, intraregional trade is not expected to rise in the near future. Deforestation will continue throughout the region with little or no regrowth outside of well-protected national parks. This study thus demonstrates that in Central America, and possibly in other regions as well, the nation is the largest extent that can be analysed. The extent of the analysis has to be determined by existing organisational units, and not by data availability or computing time.

Fig. 5 depicts the relations between model performance, spatial extent, and spatial resolution as established in this study. There is an apparent paradox

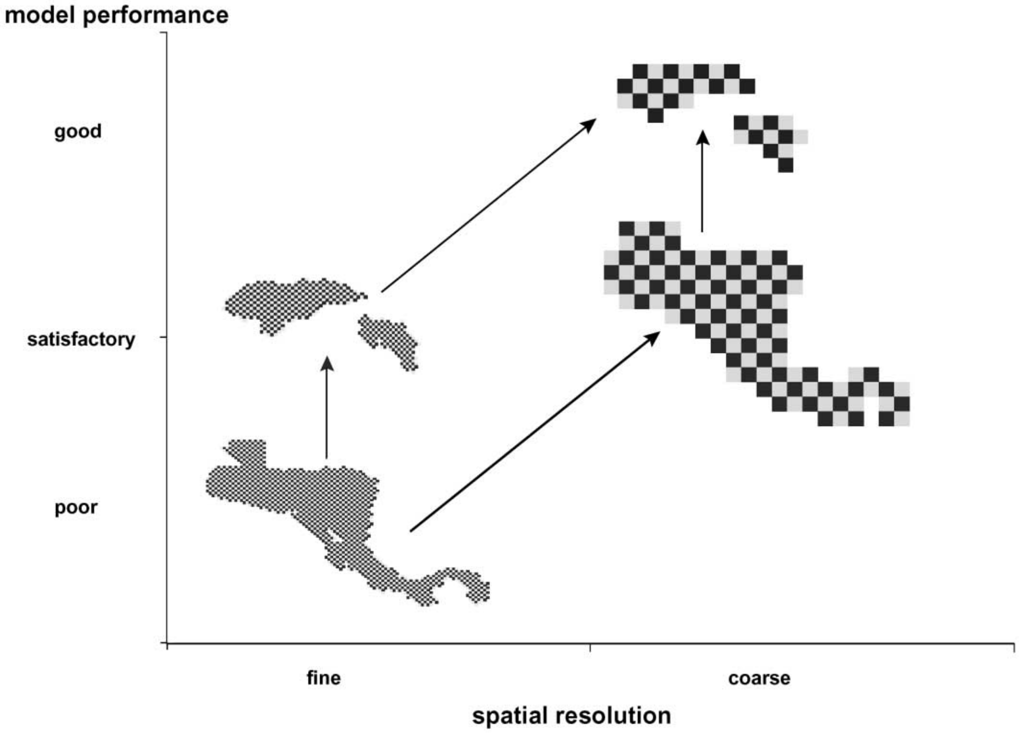


Fig. 5. Schematic representation of model performance as a function of spatial extent (region versus country, represented by Costa Rica and Honduras) and spatial resolution (represented by differently sized checkerboards).

between the decrease of explanatory power when enlarging the spatial extent and the increase of model fits when coarsening the spatial resolution, as the effect of both changes in spatial scale is a potential inclusion of more land use change processes. The observed changes in model performance nicely illustrate the difference between varying extent and resolution. By enlarging the extent from country to region in Central America, a border of a level of organisation is crossed. In the regional analysis, six differently organised units are combined in one analysis, which explains the lower model fits. By increasing spatial resolution, borders between levels of organisation might be crossed also, but those sub-national levels apparently do not have a significant influence in Central America. Aggregation effects (see Rastetter et al., 1992) and changes in variance within one level of organisation becomes major differentiators, which results in a model performance increase. Extrapolation of findings to other regions is very difficult, as information on the presence of supra-national or sub-national levels of organisation is lacking.

Our findings have implications for modelling efforts at regional or global level. In the first place, it has to be investigated whether it is necessary to create separate uniform units within a country, based on agroecological zones or planning regions, like that exist in, e.g. Costa Rica. Secondly, this paper should be a warning for global change modellers, especially those that choose to incorporate a spatially explicit analysis of land use changes, but do so in a simplified and highly aggregate manner due to data limitations. One must realise that the adoption of a limited number of world regions (e.g. IMAGE 2.1) as modelling extents will result in assumptions that could violate the actual situation. Before a realistic simulation of land use changes can be claimed (see Leemans, 1999), a thorough analysis of the effects of spatial scale on their predictions of spatial explicit land use changes need to be included.

5. Conclusions

- Various types of factors are equally important in the explanation of land use patterns in Central America. Soil, biogeophysical and demographic factors all need to be included in any analysis of the distribution of land use at coarser scales.
- Coarsening of spatial resolution does not greatly influence the composition of the set of land use determining factors, although explanatory power increases.
- The effect of changing the spatial extent on the set of land use determining factors is substantial, with an strong increase in explanatory power when reducing the extent from regional to national.
- The key assumption of the supra-national extent is that the agricultural markets are completely open, which is highly unrealistic in Central America. The nation is therefore the largest extent that can be analysed or subsequently modelled.

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