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Land use in Ecuador: a statistical analysis at different aggregation levels

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Abstract

Land use in Ecuador was investigated by means of statistical analysis with the purpose of deriving quantitative estimates of the relative areas of land use types on the basis of biogeophysical, socio-economic and infrastructural conditions. The smallest spatial units of investigation were 5 by 5 minute (9.25×9.25 km) cells of a homogenous geographical grid covering the whole country. Through aggregations of these cells, a total of six artificial aggregation levels was obtained with the aim of analysing spatial scale dependence of land use structure. For all aggregation levels independent multiple regression models were constructed for the estimation of areas within cells of the land use/cover types permanent crops, temporary crops, grassland and natural vegetation. The variables used in the models were selected from a total of 23 variables, that were considered proxies of biogeophysical, socio-economic and infrastructural conditions driving Ecuadorian land use. A spatial stratification was applied by dividing the country into three main eco-regions. The results showed that at higher aggregation levels, the independent variables explained more of the variance in areas of land use types. In most cases, biogeophysical, socio-economic as well as infrastructural variables were important for the explanation of land use, although the variables included in the models and their relative importance varied between land use types and eco-regions. Also within one eco-region, the model variables varied with aggregation level, indicating spatial scale effects. It is argued that these types of analyses can support the quantitative multi-scale understanding of land use, needed for the modelling of realistic future land use change scenarios that take into account local and regional conditions of actual land use.

Keywords: Land use; Spatial scales; Multi-scale analysis; Aggregation; Ecuador

1. Introduction

World-wide changes in land use and resulting land cover have caused important effects on natural resources through deterioration of soil and water quality, the loss of biodiversity, and by changing global climate systems (Turner II et al., 1994; Ojima et al., 1994). This has stimulated research aiming at a better understanding of the factors driving land use and cover change, and the effects of these changes on the environment. It is recognised that biogeophysical as well as human drivers have to be taken into account (Turner II et al., 1995; Bilsborrow and Okoth Ogendo, 1992; Riebsame et al., 1994). In order to support explorative modelling of future land use and cover changes and their effects, quantitative information is

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needed about the way interacting driving forces relate to (changes in) land use/cover. Because of the complex nature of these relations, empirical statistical analysis of land use/cover and its drivers has been proposed (Turner II et al., 1995; Bawa and Dayanandan, 1997; Walsh et al., 1997; Veldkamp and Fresco, 1997a). Empirical models based on these statistical relations can complement process-based land use modelling. Process-based models aim at more explanatory power but have difficulties in linking biogeophysical and human drivers. Furthermore scale problems may arise when applying point models to higher spatial scales (Veldkamp and Fresco, 1997b). Empirical explorative land use models based on the analysis of actual land use present possible scenarios that aim at a relatively limited future time scale (say 20 years), but are especially useful in situations where the actual production is still considerably below the biophysical potential, indicating strong limitations from socio-economic conditions.

It has been recognised that the type and effect of drivers of land use/cover may vary with spatial scale, because of the occurrence of patterns in land use/cover that disappear or emerge going from one scale to another (Walsh et al., 1997; Veldkamp and Fresco, 1997a). In order to investigate these scale dependent patterns in land use, an analysis at different spatial scales is necessary. Veldkamp and Fresco (1997a) have analysed land use in Costa Rica at artificial spatial aggregation levels, created by aggregating uniformly sized cells of a geographical grid. They concluded that the contribution of biogeophysical and socio-economic factors to the explanation of land use/cover in Costa Rica shows a scale dependence.

In the present study a statistical analyses is presented of current land use in Ecuador with the objective of finding quantitative estimates of (proxies of) land use/cover drivers. The methodology, a statistical analyses at different sub-national artificial spatial aggregation levels in order to investigate spatial scale effects, builds on the methodology proposed by Veldkamp and Fresco (1997a). However, some major adaptations were made in order to improve the methodology. A spatial stratification of land use through the definition of three main eco-regions was applied. Furthermore, different sets of drivers were considered at the various aggregation levels.

Ecuador was chosen for this research because it is a country with a high agro-ecological diversity. It has a dynamic and expanding agricultural land use, which has major effects on the natural resources of the country and the sustainability of land use (Southgate and Whitaker, 1994; Bebbington, 1993). In many ways Ecuador can be considered indicative for the Andean countries in general.

Strictly, land use and land cover should be separated, land cover being the biophysical state of the earth's surface and immediate subsurface, and land use involving both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation – the purpose for which the land is used (Turner II et al., 1995). However, land use and cover can often not be clearly separated. In this paper only the term land use will be used.

2. Land use in Ecuador and its potential drivers

Ecuador is a country characterised by great agro-ecological diversity. Cañadas (1983) has identified 25 Holdridge lifezones within Ecuador. The country can be divided into three broad eco-regions. The Andean eco-region consists of the north-south orientated Andean mountain range, with peaks to around 6000 m above sea level. West of this eco-region, the tropical lowlands bordering the pacific ocean comprise the coastal eco-region. East of the Andes, the Amazonian eco-region is located, still consisting mainly of tropical rainforest.

In the past, agriculture was mainly concentrated in the more densely populated Andean eco-region. Since 1900 the colonisation of the tropical lowlands has taken place especially in the coastal eco-region, first accelerated by the cacao boom at the beginning of this century and later by the banana boom in the 1950s and 1960s (Bromley, 1981). Agricultural exploitation of the Amazonian eco-region has increased especially since the 1970s, coinciding with the discovery of oil (Southgate and Whitaker, 1994). Also during the agrarian reforms in the 1960s and early 1970s, colonisation of new land as a result of population pressure was area-wise more important than redistribution of land (Zevallos, 1989).

Table 1
The 1974 and 1991 harvested area (×1000 ha) and average crop yields (Metric ton/ha) over the periods 1974–1982 and 1983–1991 for Ecuador's 12 main crops (areawise in 1991). Sources: FAO (1997) and MAG/PRSA (1994)

Crop	Land use type	Area 1974	Area 1991	Yield 1974–1982	Yield 1983–1991
Maize	Temporary crops	271.6	474.2	1.05	1.16
Coffee	Permanent crops	231.8	403.9	0.30	0.31
Cocoa	Permanent crops	221.7	332.0	0.32	0.28
Rice	Temporary crops	102.7	283.9	3.69	3.20
Banana	Permanent crops	151.8	168.5	26.94	23.16
Plantain	Permanent crops	57.9	92.2	9.02	11.40
Soybean	Temporary crops	3.1	90.7	1.46	1.80
Oil palm	Permanent crops	10.6	58.6	7.08	13.8
Barley	Temporary crops	60.8	60.3	0.85	0.83
Potato	Temporary crops	39.1	52.2	11.67	8.60
Bean	Temporary crops	66.2	51.9	0.49	0.56
Sugar cane	Permanent crops	100.8	48.9	75.66	75.26

The land use data of the agricultural census of 1974 (INEC, 1974a) and data from 1991 (INEC, 1991) show that the area of agricultural land has increased in that period by approximately 2.1 million ha, or 36% of the 1974 area. Fig. 1 shows the land use changes for the three main administrative regions. In all regions important relative increases in agricultural land use for crops have taken place, whereas fallowing of agricultural land has decreased. Especially important is the increased area dedicated to grassland, which, among others, has been caused by the growing demand of the urban population for meat and milk (Zevallos, 1989; Commander and Peek, 1986).

Table 1 indicates per hectare yields of some important crops, averaged for the periods 1974–1982 and 1983–1991. Although some care has to be taken with respect to the reliability of yield data, it seems fairly safe to conclude that no significant increase in yields is occurring.

In almost the same period, Ecuador's population as reported in the censuses has risen from 6.5 million in 1974 (INEC, 1974b) to 9.7 million in 1990 (INEC, 1990), with the percentages of urban population being 41% in 1974 and 55% in 1990, respectively. It could be concluded therefore that, at a national scale, Ecuador's need for agricultural products has mainly caused the expansion of agricultural land. So far, a development where population pressure leads to intensification, such as higher per hectare yields (Boserup, 1965) seems less important.

Actual land use in Ecuador is potentially related to a wide range of factors. Among the biogeophysical factors, obviously soil and climate have to be taken into account. General features derived from soil maps can serve as proxies for potential agricultural use. Soil texture and natural fertility indicators (including organic matter content, mineral composition and pH), yield information on workability, erosion risk, drainage and natural fertility. In Ecuador, climate characteristics are very complex with respect to their variability in time and space, with temperature regimes ranging from tropical to permanent frost, and precipitation regimes from desert-like to very humid. Annual mean temperature and annual total precipitation of climatic zones are examples of proxies for much more complex climate conditions at detailed scales. In the highly dissected Ecuadorian landscape slope steepness has importance, in combination with soil properties and climate, for soil workability and erosion risks.

Often, socio-economic data are collected and used in studies at the farm level. At higher aggregation levels (as in the present study), socio-economic variables have to be available for the total area of interest and should have the validity to serve as proxies for the much more differentiated underlying conditions. Among these proxies are demographic indicators, such as rural and urban population densities, which determine among others the availability of labour, the local need for food crops and animal products, and the

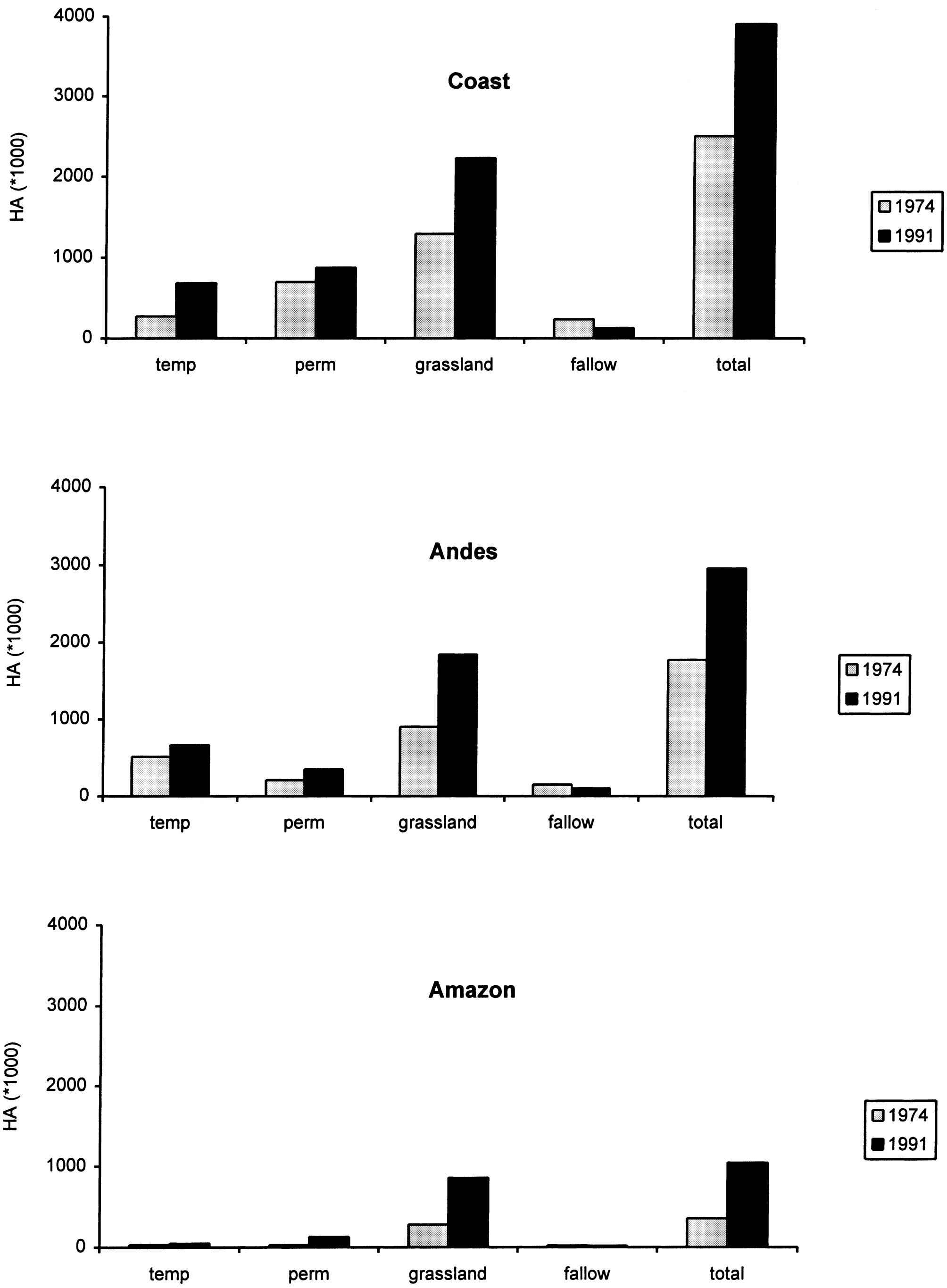

Fig. 1. Land use in 1974 and 1991 in the main administrative regions Coast, Andes and Amazon. Sources: (INEC, 1974a, 1991). Temp: temporary (annual) crops; Perm: permanent (perennial) crops; Fallow: fallow between one to five years. The region Coast consists of the provinces El Oro, Esmeraldas, Manabí, Guayas, Los Ríos, the region Andes of the provinces Azuay, Bolivar, Cañar, Carchi, Cotopaxi, Chimborazo, Imbabura, Loja, Pichincha and Tungurahua and the region Amazon of the provinces Morona Santiago, Napo, Pastaza, Zamora Chinchipe and Sucumbíos.

pressure on land (Southgate et al., 1991). The number of people working in agriculture and illiteracy levels further differentiate these broad demographic characteristics. Illiteracy can, for example, be considered an indicator of access to information and means. Poverty indicators can be of importance through their relation with investment opportunities and crop choice.

Distance to urban centres determines access to markets, relevant both for the selling of products, as well as for the access to means of production. This is further determined by proximity to infrastructure e.g. roads. Major rivers permit transportation and offer irrigation opportunities.

3. Methodology

3.1. Spatial resolution and aggregation levels

The lowest aggregation level used in this study was a homogeneous geographical grid with a grid cell size of 5 by 5 minutes (approximately 9.25 by 9.25 km), covering the Ecuadorian territory according to the protocol of Rio de Janeiro 1942, excluding the Galapagos islands. A cell was considered an Ecuadorian land cell when at least 50% of its surface was Ecuadorian territory excluding sea. The total number of Ecuadorian land cells was 2982. Biogeophysical and socio-economic data were collected and attributed to these cells. All attribute data for the cells of the base resolution were aggregated to higher artificial aggregation levels by averaging the data of 2 by 2 (=4) cells, 3 by 3 (=9) cells, 4 by 4 (=16) cells, 5 by 5 (=25) cells and 6 by 6 (=36) cells. Fig. 2 presents the six aggregation levels created this way.

3.2. Biogeophysical data

Soil attribute data were derived from the 1:1 million soil map of Ecuador (González et al., 1986). On this map 36 great groups are distinguished, which are

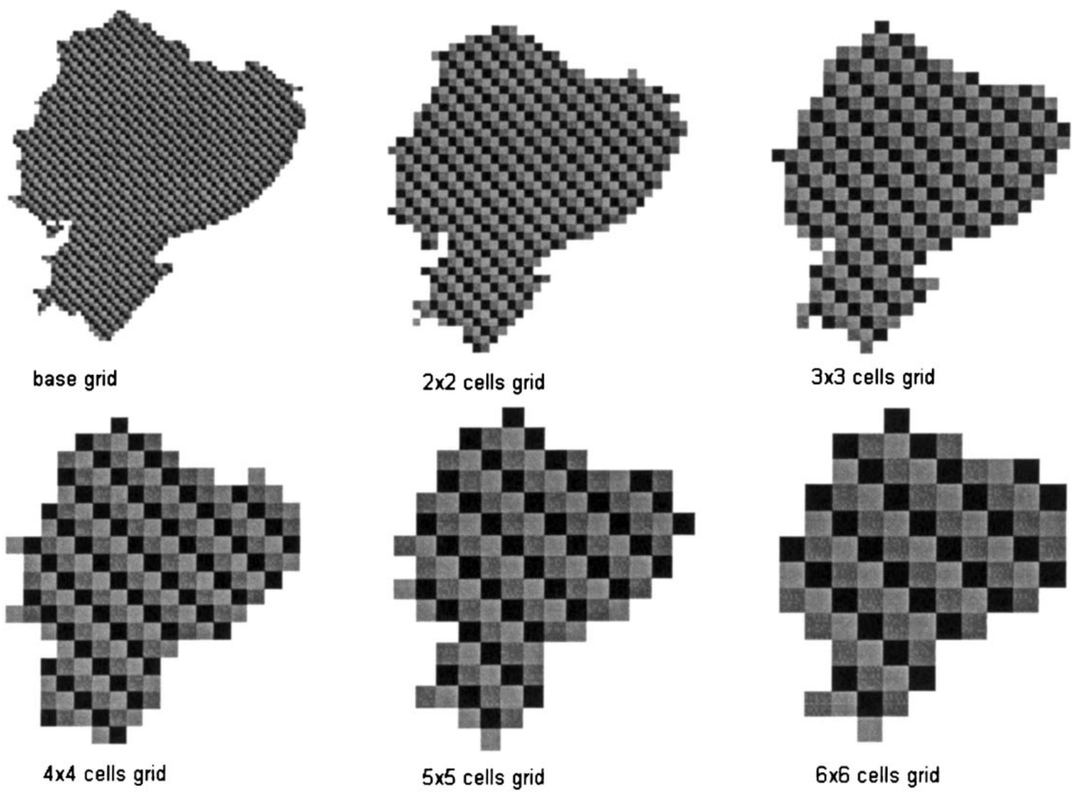

Fig. 2. The six aggregation levels.

further subdivided into 62 soil units, on the basis of parent material, climate, physiography, relief, soil texture, and chemical and mineralogical soil properties. The soil units on the soil map were matched with the base grid by assigning to each grid cell the two biggest occurring soil units with their respective surface fractions. Physical and chemical soil attribute data were linked to the soil units on the basis of map descriptions and literature, as described by De Koning et al. (1997). Three texture classes were defined on the basis of clay content (<35%; 35–55%; >55%) and for each cell the area fraction of each texture class was calculated. The same procedure was followed for three slope classes (0–8%; 8–16%; >16%). Three natural soil fertility classes (low, medium and high fertility) were determined on the basis of the soil descriptions of Beinroth (1985).

Climate data were derived from the 1:1 million bioclimatic map of Cañadas (1983). He distinguished 29 climate zones, on basis of altitude/temperature and yearly total precipitation. The climate zones on the map were matched with the base grid by assigning to each grid cell the two dominant climate zones with their respective surface fractions. In this way annual total precipitation was calculated for each cell. Mean altitude per cell was taken from a 5 by 5 minute altitude database (W. Cramer, pers. comm., 1997).

3.3. Socio-economic data

Ecuador's administrative division consists of provinces, subdivided into cantons which are further subdivided into parishes. In 1990 the number of provinces (excluding the Galapagos islands) amounted to 20 and the number of cantons 162. Ecuador's urban parishes are all located in the capitals of the cantons. The rural population is located in the periphery of these capitals and in rural parishes (738 rural parishes existed in 1990).

Population census data at the parish level of 1990 were used (INEC, 1990). On basis of 1:250,000 maps with administrative regions, each cell was allocated the (maximally) three main occurring rural parishes (or urban periphery) with their respective surface fractions. In this way the population of all rural parishes was allocated to the grid cells. The urban population of canton capitals was allocated to the cells where these capitals are located. Population data were corrected with the 1991 projections (INEC, 1993) in order to obtain the 1991 projected data at the level of cells.

Next to total numbers of rural and urban population, census data were used to determine the percentage of the economically active population working in agriculture, and the level of illiteracy. Furthermore, for 1990, data were available on the percentage of people living in poverty at the parish level in 1990 (Larrea et al., 1996). The percentages of illiteracy, population working in agriculture and poverty of 1990, were considered to be representative for the 1991 situation.

3.4. Markets and infrastructure

In order to account for the accessibility to urban markets, the distance to the nearest urban centre was calculated through a standard distance operation in a geographical information system (GIS) using the centres of grid cells as reference points. Similarly, the distance to the nearest main roads and rivers was calculated with a GIS distance operation, using vector maps of the main roads and rivers.

3.5. Land use data

The current yearly agricultural statistics are collected by means of stratified sampling by the National System for Agricultural Statistics (SEAN). SEAN data for 1991 (INEC, 1991) were used, containing information on 65,415 farmers in 3137 sample sites. Data of sample sites were related to grid cells, thus constructing a land use map. When more than one sample site was found within a grid cell, data from these sites were averaged. In the present study the four main land use types were used: permanent (perennial) crops, temporary (annual) crops, grassland and natural vegetation. Instead of characterising land use in a cell by allocating the dominant land use type, for each cell the percentages of each of the land use types occurring in the cell was used for further analysis. Fig. 3 shows the land use maps constructed this way.

3.6. Stratification

A stratification was applied by dividing the country into three broad eco-regions. The eco-region Andes

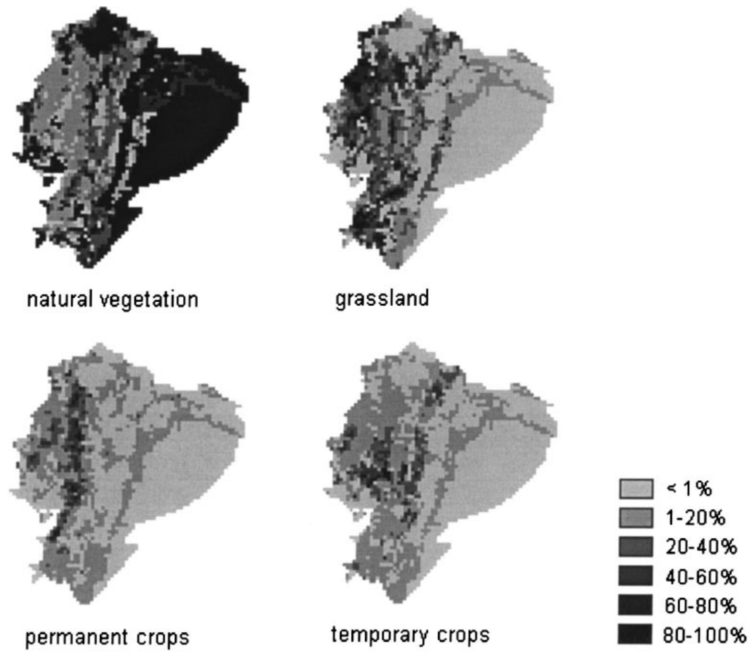

Fig. 3. Area distribution of natural vegetation, grassland, permanent crops and temporary crops.

was defined as all cells above of an altitude of 1000 m.a.s.l. (meters above sea level), following the zonification of Frère et al. (1975). The remaining broad eco-regions are the Coast and Amazon (Fig. 4). This division is slightly different than the one used in agricultural statistics, which is based on provinces (see Fig. 1), but makes more ecological sense. The stratification leads to a general division between typical highland crops like barley, broad bean, soft maize and potato, and crops cultivated at lower altitudes, like cacao, rice, banana, plantain, soybean, hard maize and African palm. Also coffee is mainly cultivated below 1000 m.a.s.l. in Ecuador. Common beans are grown both below and above 1000 m.a.s.l. The number of cells at the six aggregation levels was for eco-region Coast 931, 248, 106, 60, 38 and 28, respectively, for eco-region Andes 1105, 279, 120, 70, 45 and 29, respectively, and for eco-region Amazon 946, 237, 107, 60, 39 and 30, respectively.

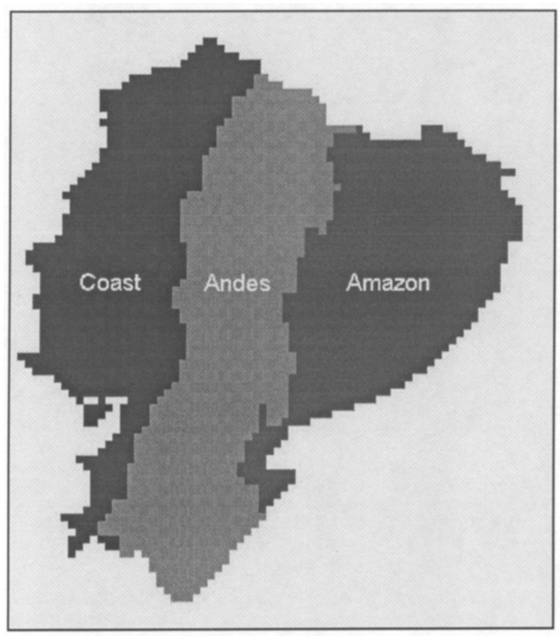

Fig. 4. The stratification into three eco-regions.

3.7. Statistical analysis

The possible biogeophysical and socio-economic drivers of Ecuadorian land use in 1991 were investigated with multiple regression methods. Four main land use types were taken into account: permanent crops, temporary crops, grassland and natural

Table 2
Variables included in the stepwise regression analysis

Variable	Explanation	Unit
text1	Percentage soils with texture class 1 (<35% clay)	–
text2	Percentage soils with texture class 2 (35–55% clay)	–
text3	Percentage soils with texture class 3 (>55% clay	–
slope1	Percentage soils with slope class 1 (<8%)	–
slope2	Percentage soils with slope class 2 (8–16%)	–
slope3	Percentage soils with slope class 3 (>16%)	–
fert1	Percentage low fertility soils	–
fert2	Percentage medium fertility soils	–
fert3	Percentage high fertility soils	–
alt	Altitude	m.a.s.l.
prec	Total annual precipitation	mm
urbdis	Distance to nearest urban centre	km
roaddis	Distance to nearest road	km
riverdis	Distance to nearest river	km
totpop	Total population per surface area	km^{-2}
rurpop	Rural population per surface area	km^{-2}
urbpop	Urban population per surface area	km^{-2}
pov-tot	Percentage of total population living in poverty	–
pov-rur	Percentage of rural population living in poverty	–
illit-tot	Percentage of total population that is illiterate	–
illit-rur	Percentage of rural population that is illiterate	–
agric-tot	Percentage of total population working in agriculture	–
agric-rur	Percentage of rural population working in agriculture	–

vegetation. The analysis was done independently at the six aggregation levels and the three eco-regions.

The most important land use drivers (independent variables) for the four land use types (dependent variables) were selected by means of stepwise regression, using the 0.05 significance criterion for each independent variable. Table 2 lists the total set of variables that was included in the stepwise regression (temperature is not included because of its direct correlation with altitude in Ecuador). A maximum of seven variables was selected, because only slight improvements of models fits were obtained with more variables. At each aggregation level an independent set of variables was selected this way. This contrasts with the approach of Veldkamp and Fresco (1997a) for Costa Rica, who used the same set of six variables at each aggregation level.

The selected variables were then used in multiple regression models. Of these models the adjusted coefficient of determination (r^2) is a measure for the amount of variation in the percentage of the specific land use type in the spatial units that can be explained by the model variables. The standardised betas indicate the number of standard deviation changes in the dependent variable associated with a standard deviation change in the independent variable if all other variables are held constant. They are therefore indicative for the relative importance of a variable for land use change in a given regression equation.

4. Results

Fig. 5 presents graphically the adjusted coefficients of determination (r^2) of the multiple regression models for the four land use types and six aggregation levels, for the eco-regions Coast, Andes and Amazon. All models were significant at the 0.001 level. The general pattern in all three eco-regions is that of an increasing r^2 with higher aggregation levels, as expected given the reduction of extreme values.

In eco-region Coast, the model explains 24% to 46% of the variance of the land use types at the 1×1 aggregation level, and this increases to 58% to 87% at the 6×6 aggregation level. The best model fits are

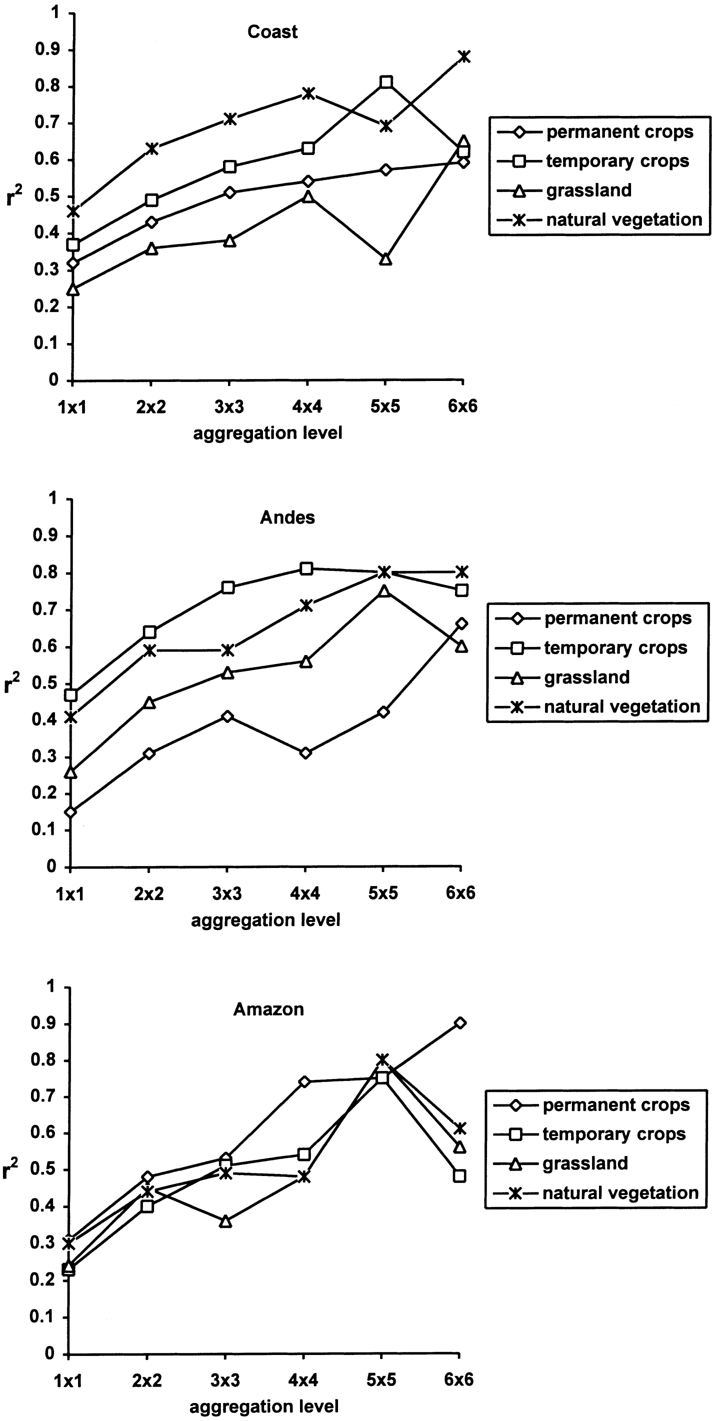

Fig. 5. Coefficient of determination (r^2) of multiple regression models for four land use types at six aggregation levels for the eco-regions Coast, Andes and Amazon.

Table 3
Multiple regression models at six aggregation levels for area permanent crops, temporary crops, grassland and natural vegetation in the eco-region Pacific Coast. stb: standardized regression coefficients. Asterisk: see text

1×1 grid		2×2 grid		3×3 grid		4×4 grid		5×5 grid		6×6 grid	
param	stb	param	stb	param	stb	param	stb	param	stb	param	stb
Permanent crops											
text1	0.42	text1	0.52	text1	0.66	text1	0.57	fert1	−0.56	text2	−0.51
roaddis	−0.30	alt	−0.46	alt	−0.57	alt	−0.54	agric-rur	0.49	agric-rur	0.44
alt	−0.30	roaddis	−0.38	agric-tot	0.43	slope3	0.51*	slope2	−0.33	roaddis	−0.39
slope3	0.26*	slope3	0.36*	slope3	0.41*	roaddis	−0.45	illit-rur	−0.30		
agric-rur	0.22	agric-rur	0.26	urbdis	−0.38	agric-tot	0.43				
fert3	0.15	fert3	0.18	roaddis	−0.32	pov-tot	−0.38				
illit-rur	−0.11	illit-rur	−0.14	illit-tot	−0.26	fert3	0.32				
Temporary crops											
fert3	0.26	fert3	0.33	rurpop	0.60	rurpop	0.38	illit-rur	0.52	rurpop	0.68
illit-rur	0.23	slope3	−0.28	slope3	−0.31	fert3	0.38	rurpop	0.50	agric-rur	0.41
riverdis	−0.21	rurpop	0.28	fert2	−0.23	slope3	−0.23	fert2	−0.39		
slope3	−0.22	illit-rur	0.27	illit-rur	0.21	illit-rur	0.21	roaddis	−0.32		
rurpop	0.19	riverdis	−0.23	alt	0.19*	riverdis	−0.21	slope3	−0.30		
prec	−0.16	prec	−0.22								
roaddis	−0.08	alt	0.15*								
Grassland											
roaddis	−0.32	roaddis	−0.44	roaddis	−0.55	roaddis	−0.79	slope1	−0.43	agric-rur	0.80
slope3	0.26	slope3	0.32	text3	0.33	text1	−0.67	roaddis	−0.42	fert1	−0.76
fert1	−0.19	text3	0.25	riverdis	−0.31	prec	0.67*	fert1	−0.29	slope3	0.73
text3	0.16	riverdis	−0.25	slope3	0.24	fert2	0.52			alt	−0.70
riverdis	−0.15	fert1	0.25	fert2	0.22	agric-rur	0.52			illit-rur	−0.55*
totpop	−0.11										
urbdis	−0.10										
Natural vegetation											
roaddis	0.45	roaddis	0.49	roaddis	0.50	roaddis	0.55	roaddis	0.50	agric-rur	−0.68
fert1	0.26	fert1	0.31	fert1	0.25	agric-rur	−0.34	fert1	0.38	fert1	0.58
riverdis	0.16	riverdis	0.28	agric-rur	−0.20	fert1	0.34	agric-rur	−0.35	roaddis	0.43
agric-rur	−0.16	text3	−0.20	rurpop	−0.20	riverdis	0.22			alt	0.34
alt	0.13	rurpop	−0.12	riverdis	0.19	text3	−0.17			slope3	−0.34*
slope3	−0.12*	slope2	0.12*	text3	−0.12					illit-rur	0.20
urbdis	0.11										

found for natural vegetation and temporary crops, except at the 6×6 level, where grassland is modelled slightly better than temporary crops. The shape of the curves is somewhat disturbed at the 5×5 and 6×6 aggregation levels, where (except for permanent crops) the models seem to become more unstable, probably because of the amount of values (cells) available for analysis which is becoming progressively lower. This is less in the case of eco-region Andes. Here, model fits range from 15% to 47% at the lowest aggregation level, to 60% to 80% at the highest aggregation level. In this eco-region temporary crops are explained best, followed by natural vegetation, grassland and permanent crops. In the Amazon, an increase of r^2 is seen up to the 5×5 aggregation levels where between 75% and 80% of the variance is explained. At the highest aggregation level model fits decrease quite strongly for all land use types except permanent crops.

Tables 3–5 show for the three eco-regions the variables and their standardised betas (stb's) in the regression models. Table 2 gives the description of the variable names. The stb's can be considered as a measure for the relative importance of a variable

Table 4
Multiple regression models at six aggregation levels for area permanent crops, temporary crops, grassland and natural vegetation in the eco-region Andes. stb: standardized regression coefficients. Asterisk: see text

1×1 grid		2×2 grid		3×3 grid		4×4 grid		5×5 grid		6×6 grid	
param	stb	param	stb	param	stb	param	stb	param	stb	param	stb
Permanent crops											
alt	−0.32	alt	−0.44	alt	−0.66	alt	−0.49	alt	−0.84	alt	−0.73
pov-rur	−0.16	pov-tot	−0.27	pov-rur	−0.44	fert3	0.30	pov-tot	−0.58	fert3	0.68
fert3	0.12	fert3	0.24	slope2	0.28	urbdis	−0.26	illit-tot	0.38	text2	−0.25
slope2	0.11	slope2	0.17	text2	−0.20*						
agric-rur	0.11	agric-rur	0.17	agric-rur	0.20						
urbdis	−0.09										
text2	−0.06*										
Temporary crops											
illit-rur	0.52	rurpop	0.38	rurpop	0.49	text1	0.80	rurpop	0.56	rurpop	0.53
illit-tot	−0.34	illit-rur	0.21	illit-rur	0.28	rurpop	0.70	text2	0.55	illit-rur	0.39
rurpop	0.29	urbdis	−0.15	slope2	0.23	fert2	−0.49	text1	0.36	urbdis	−0.26
prec	−0.13	slope3	−0.13	urbdis	−0.15	text2	0.45	illit-rur	0.33		
fert3	0.13	fert3	0.13	text2	0.11	urbpop	−0.28*				
slope3	−0.12	prec	−0.12			illit-rur	0.22				
urbdis	−0.12										
Grassland											
alt	−0.29	pov-tot	−0.34	alt	−0.48	fert3	0.38	pov-tot	−0.47	fert3	0.73
pov-rur	−0.22	fert3	0.34	pov-tot	−0.42	alt	−0.33	fert3	0.47	alt	−0.43
fert3	0.16	alt	−0.26	fert3	0.31	pov-tot	−0.32	alt	−0.35		
urbdis	−0.15	urbdis	−0.24	prec	−0.21	prec	−0.28	text2	0.34		
prec	−0.12	slope3	0.19*	riverdis	0.12	illit-tot	−0.23	slope3	0.26*		
roaddis	−0.08	text2	0.13					roaddis	−0.23		
riverdis	0.08	riverdis	0.12								
Natural vegetation											
pov-tot	0.21	illit-rur	−0.22	pov-tot	0.29	pov-tot	0.28	text2	−0.40	fert3	−0.50
illit-tot	−0.20	roaddis	0.18	roaddis	0.25	roaddis	0.28	fert3	−0.36	slope2	−0.38
roaddis	0.16	prec	0.16	fert3	−0.23	prec	0.26	text1	−0.32	illit-rur	−0.21
urbdis	0.15	fert3	−0.16	prec	0.19	fert3	−0.24	roaddis	0.27		
prec	0.13	urbdis	0.15	illit-tot	−0.18	riverdis	−0.15	illit-rur	−0.23		
fert3	−0.12	riverdis	−0.13	riverdis	−0.15			pov-rur	0.21		
riverdis	−0.09							riverdis	−0.19		

for changes in the dependent variable in a given equation. The stepwise regression procedure corrects for co-linearity, excluding variables that are strongly correlated with others. However, remaining weak correlation limits the interpretation of a single independent variable with respect to its one to one correlation with the dependent variable. Even the sign of the regression coefficient may be the opposite of the sign in a one to one correlation matrix. Cases where this occurs have been indicated with an asterisk. The results will be described in more detail for the three eco-regions independently.

4.1. Coast

4.1.1. Permanent crops

At the lower aggregation levels the area with permanent crops is mainly explained by the contributions of soil texture, distance to roads, altitude and slopes (Table 3). At the highest aggregation levels the number of included variables becomes smaller. The socio-economic variable agricultural labour force is the only one that is included in all models.

Interpreting the results, the association of permanent crops with light textured soils is likely to be

Table 5
Multiple regression models at six aggregation levels for area permanent crops, temporary crops, grassland and natural vegetation in the eco-region Amazon. stb: standardized regression coefficients. Asterisk: see text

1×1 grid		2×2 grid		3×3 grid		4×4 grid		5×5 grid		6×6 grid	
param	stb	param	stb	param	stb	param	stb	param	stb	param	stb
Permanent crops											
fert1	−0.32	totpop	0.49	totpop	0.62	totpop	0.59	totpop	0.78	rurpop	0.93
rurpop	0.23	fert2	0.25	fert2	−0.27	alt	−0.26*	fert1	−0.28	slope2	−0.19
fert3	−0.22*	urbdis	−0.12	prec	0.18	fert2	0.21	agric-rur	0.18	fert1	−0.16
totpop	0.21	alt	−0.11*			urbdis	−0.19			alt	−0.13*
urbdis	−0.15	fert3	0.11			riverdis	−0.14				
alt	−0.11*	prec	0.10								
riverdis	−0.08										
Temporary crops											
rurpop	0.29	rurpop	0.41	prec	0.49	rurpop	0.52	fert2	0.73	rurpop	0.58
prec	0.23	prec	0.35	rurpop	0.48	prec	0.42	urbdis	−0.25	prec	0.34
fert1	−0.17	fert1	−0.29	fert1	−0.48	fert1	−0.33				
slope3	0.11*	slope3	0.18*	slope3	0.30	slope3	0.28				
agric-rur	0.09	agric-rur	0.14	text3	0.21*						
riverdis	−0.08										
totpop	0.08										
Grassland											
rurpop	0.21	fert2	0.53	fert2	0.38	prec	0.39	fert2	0.56	fert2	0.41
urbdis	−0.20	prec	0.38	prec	0.33	text2	−0.38	urbpop	0.34	prec	0.41
fert1	−0.18	fert1	−0.34	illit-tot	−0.30	pov-tot	−0.36	alt	0.19	pov-tot	−0.38
illit-rur	0.18*	text1	−0.26*					riverdis	−0.15		
alt	0.17	pov-tot	−0.22								
prec	0.13	slope1	−0.20								
pov-rur	−0.12	alt	0.12								
Natural vegetation											
rurpop	−0.30	prec	−0.45	prec	−0.52	prec	−0.42	urbpop	−0.56	prec	−0.50
fert1	0.24	fert1	0.36	fert1	0.39	fert2	−0.35	prec	−0.47	pov-tot	0.40
illit-rur	−0.24*	slope3	−0.29	rurpop	−0.27	pov-tot	0.32	slope1	0.38	fert2	−0.35
urbdis	0.22	rurpop	−0.24	slope3	−0.22			fert1	0.33		
prec	−0.18	fert2	−0.18	pov-tot	0.21						
alt	−0.15	pov-tot	0.16								
slope3	−0.15	illit-rur	−0.14*								

related to the better drainage of these soils, which is especially beneficial in the low lying flat river plains (the direct correlation between permanent crops and both altitude and steep slopes is negative). Furthermore, cultivation of permanent crops (most of which are cash crops in this region) is associated with proximity to roads, a high share of people working in agriculture and low percentages of illiteracy.

4.1.2. Temporary crops

Socio-economic variables become increasingly important at higher aggregation levels (Table 3). Of these variables, the agricultural labour force is included only at the highest aggregation level. Of the biogeophysical variables, fertility and slope are contributing most to the model. Distance to rivers and roads both occur in the models but do not show a clear relation with aggregation level.

In the eco-region coast, temporary crops are cultivated relatively more in areas with fertile soils, with few steeply sloping terrain and in proximity to rivers and roads. Furthermore, these crops are grown more in areas with high rural population densities and higher illiteracy. Fewer temporary crops are grown in wetter areas, which are especially found in the northern part of the Pacific coast.

4.1.3. Grassland

For grassland, aggregation level does not produce a very clear pattern (Table 3). At the highest aggregation level rural illiteracy and altitude are selected, variables that are not selected at the lower levels. Up to the 5×5 level, the distance to roads is a major variable in the models. Soil related variables also rank high. River distance is only included at the three lowest aggregation levels. As with permanent and temporary crops, the number of people working in agriculture is important at the highest aggregation level.

Grassland is related to dissected terrain, the likely reason being that steep slopes present more difficulties for the cultivation of permanent and temporary crops. Grassland is associated with medium and high fertility soils in the proximity of roads and, to a lesser extent, rivers.

4.1.4. Natural vegetation

In the models for the area natural vegetation, the number of people working in agriculture, distance to roads and soil fertility contribute strongly to the models, whereas the distance to rivers only contributes up to the 5×5 level (Table 3). The contributions of slope and altitude are very variable, and illiteracy is only selected at the highest aggregation level.

Natural vegetation is clearly associated with areas less favourable for agriculture: distant from roads, rivers and urban centres, and on low fertility soils. Furthermore, natural vegetation is related to low population densities, relatively few people working in agriculture, and higher illiteracy rates.

4.2. Andes

4.2.1. Permanent crops

The number of variables in the models for permanent crops decreases progressively with the aggregation level, leaving only three biogeophysical variables in the model for the highest aggregation level (Table 4). In all models, the variable contributing most dominantly is altitude. The highest ranking socio-economic variable is total poverty, though it is not included in the 4×4 and 6×6 models. In most models soil fertility and texture is included, whereas the number of people working in agriculture is only included at the three lowest aggregation levels. The distance to urban centres contributes in just two models.

Permanent crops in the Andes are mostly cultivated at lower elevations because of climatic requirements. Next to coffee, the majority are fruit trees. These crops are furthermore associated with relatively well endowed areas with less poverty, fertile soils and, though less clear, close to urban centres. A relation is found with a relatively high percentage of the rural population working in agriculture.

4.2.2. Temporary crops

The socio-economic variables in the models for temporary crops are population density and illiteracy (Table 4). At the highest level no biogeophysical parameters are included in the model. At the lower levels, soil texture and fertility as well as slope class are selected. Precipitation is only included at the lowest two levels and distance to urban centres only at the lowest three and highest aggregation level.

Temporary crops in this eco-region are mostly subsistence crops, associated with high rural population densities and high illiteracy. This land use type is related with light textured and medium textured soils.

4.2.3. Grassland

As for permanent and temporary crops in this eco-region, there is a tendency towards models with fewer variables at higher aggregation levels (Table 4). Altitude, poverty, and soil fertility are the most important variables at the first five levels. As for permanent crops in this eco-region, only biogeophysical variables are included at the highest aggregation level.

Grassland in this mountainous eco-region is associated with lower altitude and relatively fertile soils, in areas with relatively less poverty not far from roads and urban centres.

4.2.4. Natural vegetation

Also for natural vegetation, the number of variables decreases with aggregation level (Table 4). At the highest level only three (biogeophysical) variables are left (but the model still has a rather high r^2, see Fig. 5). The percentage of the total population living in poverty is a high ranking variable at the first four aggregation levels. The other variables and their relative stb's vary quite strongly among the six models.

As expected, natural vegetation is more dominant in economically poor areas, on poor soils and further away from roads and cities. Contrary to the eco-region coast, more natural vegetation is found close to rivers. The positive relation with precipitation is probably the result of the natural areas along the outer slopes of the Andes receiving higher rainfalls.

4.3. Amazon

4.3.1. Permanent crops

Population density (rural or total) and soil fertility rank high in all models (Table 5). Distance variables are included at the lowest two and the 4×4 aggregation level. Agricultural labour force of the rural population is only included in the 5×5 model.

Permanent crops are associated with places with higher population densities and medium fertility soils. As expected in this region, more permanent crops are grown close to rivers, roads and cities, although this is not seen in all models.

4.3.2. Temporary crops

For temporary crops in all models except one, rural population density and precipitation are the highest ranking variables (Table 5). At the lower aggregation levels slope and agricultural labour force are included but river distance is only selected in the 1×1 model.

As with permanent crops, temporary crops are related to higher population densities and precipitation. Temporary crops are negatively related with poor soils. For small areas a positive relation is found with agricultural labour force and proximity to rivers.

4.3.3. Grassland

For grassland, soil fertility, precipitation and slope are included in most models (Table 5). At least one of the socio-economic variables related with population densities, poverty or illiteracy is included in the models but there is not a clear pattern with aggregation level. Distance variables are included in the 1×1 and 4×4 models.

Relatively more grassland is grown in the Amazon on medium fertility soils under relatively high precipitation, and in areas with relatively high population densities and relatively little poverty and illiteracy rates.

4.3.4. Natural vegetation

Variables selected in all models are soil fertility and precipitation (Table 5). Urban distance was only selected for the 1×1 model. In most models slope is also included and at the highest three aggregation levels the agricultural labour force. Of the socio-economic variables, rural population density and illiteracy are included at the lower aggregation levels and poverty is included in most models.

Natural vegetation is associated with low fertility soils and low population densities in areas with relatively less high precipitation and with relatively more illiteracy and poverty.

5. Discussion

The statistical analysis of Ecuadorian land use has resulted in significant multiple regression models for all combinations of land use type, eco-region and aggregation level. In most cases the models give rather satisfying fits, taking into account the highly complex nature of agro-ecosystems and the limited number of variables used. Not only the r^2 and the variables selected in the multiple regression models vary with the aggregation level, but also the standardised betas of the variables. In most models, biogeophysical as well as socio-economic or infra-structural variables are selected. Clear differences exist between land use types within each eco-region and between eco-regions.

The results quantify the structure of Ecuadorian land use. In the Pacific Coast large areas of export crops (banana, coffee, cacao) are grown. For most of the permanent crops (especially banana) proximity to infrastructure and good soil conditions are important. Generally (though less so for coffee) they are associated with better socio-economic conditions (Larrea et al., 1988). Irrigation is widely practised in order to overcome the dry conditions in the south. Important temporary crops in the Pacific coast are rice, soybean and hard maize. These last two crops are closely related to the agro-industry (Cuvi and Urriola, 1988). Soybean cultivation is rather concentrated, with hard maize grown in a more dispersed way.

Remaining natural vegetation is mainly located in the north (Esmeraldas) and along the Andean footslopes. The results of statistical analysis for the Pacific Coast confirm the occurrence of permanent crops in the areas where the biogeophysical conditions are favourable. However, in these areas competition exists with temporary crops. The results illustrate the association of permanent crops with relatively better socio-economic conditions, through the negative relation with illiteracy. Grassland is mainly different in its association with dissected terrain, because of a relative advantage compared with crop cultivation in those areas.

In the eco-region Andes, permanent crops are mainly fruit crops grown in the warmer valley bottoms and some coffee at the outer slopes of the Andes. Export crops are relatively unimportant compared with the Pacific Coast, and most temporary crops are traditional food crops (potato, beans, soft corn and barley) and vegetables, produced for on-farm consumption and the internal market. Especially after the agrarian reforms, the cultivation of these traditional food crops has in large parts of the Andes moved to the marginal areas, being grown at small farms (Bebbington, 1993). An exception is for example, the northern province of Carchi where potato is grown under relatively good conditions and with the highest yields of the country. Increasing demands for meat and milk have caused an important increase in grassland at relatively large holdings in the valley bottoms and in newly colonised areas (Schodt, 1991; Commander and Peek, 1986). The statistical relation of permanent crops with low altitudes (warmer) and fertile soils accords with expectations, as well as lower poverty levels. The cultivation of temporary crops in marginal areas is not clearly reflected in the biogeophysical variables but might be illustrated by the association with rural illiteracy. Especially strong is the relation of these crops with high rural population densities, which probably reflects the small farm sizes.

The Amazon region is being affected by agricultural colonisation as a result of high pressure on agricultural land in the Andes and Pacific Coast, a process that has been stimulated by oil exploitation (Southgate and Whitaker, 1994). Especially affected by land clearing is the north-eastern part of the Amazon. A wide diversity of land use patterns exists and many farms still contain significant areas of natural forest (Pichón, 1997). Although the most predominant agricultural land use type is grassland, a range of permanent and temporary crops are grown. Rural settlement is attracted by roads and populated areas, as well as by the presence of good soils (Southgate et al., 1991; Pichón, 1997). This is confirmed by the statistical analysis at the lowest aggregation level where permanent crops, temporary crops and grassland are negatively associated with poor soils and positively by high population densities. Furthermore, proximity to rivers and urban centres is important. At the highest aggregation levels other patterns appear, where distances to urban centres, roads and rivers are less decisive.

In comparison with results for Costa Rica (Veldkamp and Fresco, 1997a) it can be concluded that the r^2 values obtained for comparable land use types, were higher for Ecuador. This is related to the fact that for Ecuador models with different independent variables were considered at the six aggregation levels. The use of different variables in the models has the disadvantage that comparison between models is more difficult. The advantages are that the inclusion of other variables further illustrates the effects of aggregation and gives better model fits.

Some caution has to be taken when interpreting the results of such a statistical analysis. The models should in the first place be appreciated for their multi-variable descriptive and predictive power. In the explanation of the models causality is not always easy to verify, though case studies can support the interpretation of the results. Although multiple regression models are more commonly applied at household and national levels, this technique has been much less applied for the analysis of agro-ecosystems at intermediate aggregation levels. Furthermore research has often focused on either the biogeophysical or socio-economic characteristics of agro-ecosystems. In order to further enforce the theoretical frameworks for the description and explanation of biogeophysical and socio-economic drivers of land use at different aggregation levels more research in different geographical regions will be necessary. This is especially necessary as the nature of the studied system prevents intervention studies being carried out. A reproducible quantitative method such as presented here allows for comparative studies.

Care is needed with a direct comparison between land use types and single independent variables. The multi-dimensional space made up by all the independent variables can, in analogy with ecosystems theory (Odum, 1994), be considered the niche for certain agro-ecosystems. It is the specific combination of all these variables that create the conditions for agro-ecosystems to express themselves. These niches do not only depend on spatial scales, but are also dynamic in time. In this study only one year was investigated because of limitations in data availability. Time series can be a valuable extension of the current study.

With regards to data quality further improvements can be expected with the rapid progress in availability of large data bases and standardisation of censuses. Especially data obtained from remote sensing can complement data from censuses (Skole and Tucker, 1993). In the case of Ecuador, a new analysis should be done after the publication of a new complete agricultural census which will be available in a few years. This could especially improve data for the Amazon region where land use is highly dynamic and current data quality is probably poor as a result of problems of access and the difficulties in clearly classifying land use because of the complex combination of agricultural land use and natural vegetation.

An analysis of land use as presented in this study, offers scope for implementation in multi-scale land use change models (Veldkamp and Fresco, 1996). For Ecuador a model will be developed for the exploration of possible future land use developments by using different scenarios for changes in population, crop yields, international market situations, food patterns and changes in natural resources. In order to be able to develop such a model, quantitative insight in the structure of land use at different aggregation levels is necessary. The results presented in this study offer a basis for such insights.

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