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QUANTIFICATION OF LAND-USE DYNAMICS: AN ILLUSTRATION FROM COSTA RICA

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ABSTRACT

In many cases, studies dealing with land degradation require the quantification of land-use dynamics. Although research has been carried out to describe land-use dynamics and its driving forces, very little has been done on the recognition of indicators for the quantification of land-use dynamics. This article presents and discusses three different indicators recognised during a Costa Rican case-study: (1) a single-time analysis of spatial patterns; (2) standard Markov chains with a soil-type modifier; (3) geo-referenced Markov chains with indices for size, shape and land cover in neighbouring polygons. The first indicator is applied to a study area of 2942 km^2 in the northeast of Costa Rica for which 1992 aerial photographs are available. Spatial patterns of land cover can only be related to land cover modifications when good insight into the colonization history exists. For the study area, clear land-use sequences have been found. Both standard and geo-referenced Markov chains have been calculated for a smaller pilot area of 151 km^2 for which aerial photographs taken on five different dates area available. Clear differences in probabilities are found for soil type and polygon size. For the shape and boundary index, no clear relations were found in the pilot area. The quantification of land-use dynamics using these kinds of indicators is necessary for the comparison of regions and for land degradation modelling.

KEY WORDS Costa Rica; GIS; land cover; land-use dynamics; Markov chains

INTRODUCTION

Land degradation is often initiated by changes in land cover resulting from human land use rather than natural processes. Therefore, changes in land use are increasingly seen as an important issue at global as well as regional scales (Turner, *et al.*, 1994). Studies of land-cover conversion (i.e. the change from one cover class to another) as well as land-cover modification (i.e. changes within a given land-cover class) have been carried out in many areas (e.g. Brouwer and Chadwick, 1991; Houghton, *et al.*, 1991; Reiners, *et al.*, 1994; Garrity and Agustin, 1995). Although there is knowledge of the biophysical drivers of land use (based on well-known methods from land evaluation; Van Diepen, *et al.*, 1991), which is much more developed than that of socio-economic drivers (Bilsborrow and Okoth-Ogendo, 1992; Veldkamp and Fresco, 1995), many aspects of land-use change remain poorly understood. Adequate indicators to quantify land-use dynamics (i.e. land-cover conversion and modification over time) are seldom available. As a result, it is very difficult to compare rates of change between different areas and periods.

Fortunately, aerial photographs, satellite imagery and geographical information systems (GIS) now facilitate more frequent inventories and bring the analysis of land-use dynamics within reach of many more researchers. In view of the rapidly growing interest in spatial and temporal analysis using GIS (Langran, 1992; Fotheringham and Rogerson, 1994), it is all the more surprising that so far little work has been done on land-use dynamics indicators. Drawing on a case-study in Costa Rica, this paper reviews an existing method for dealing with temporal changes, and elaborates two new alternative methods and compares the outputs. The three methods are as follows.

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(1) A single-time analysis of spatial patterns based on qualitative knowledge of temporal patterns of land-use evolution. This method is new, and has been included to demonstrate the potential of a dynamic analysis based on a data set of one observation date.
(2) A more-or-less standard approach using Markov chains (Jansen, 1994) to describe the probabilities of occurrence of successive land-use changes. This method has been refined a little by including a stratification with soil type as a probability modifier.
(3) A new adaptation of the Markov chain method which includes a geographical analysis to relate changes in land use to probabilities based on the shape and size of polygons and land use in neighbouring polygons. This method reflects the observations that (a) land-cover conversion of a polygon often starts from adjacent polygons, and (b) there is a relationship between polygon shape and land use (e.g. riverside forests), and between shape and speed of conversion ('narrow strips' are 'broken through' more frequently).

The first method is elaborated for a study area in the perhumid tropical lowlands in the northeast of Costa Rica (Figure 1). The second and third methods are elaborated for a smaller pilot area for which land-cover data from several years were available. Because of rapid rates of demographic and land-cover change in the case-study area, this provides an interesting test site for studying land-use dynamics.

Colonization in the study area started approximately 100 years ago. As a result, most of the primary forest has disappeared. Nevertheless, both land-cover conversion and land-cover modification through human land use continue to take place. Although several studies of land-use dynamics have been carried out for the area, they were mainly focused on deforestation trends (Sader and Joyce, 1988; Veldkamp, *et al.*, 1992). The successive colonization of the region induced by the construction of a railroad can be characterised by a number of typical land-use modifications.

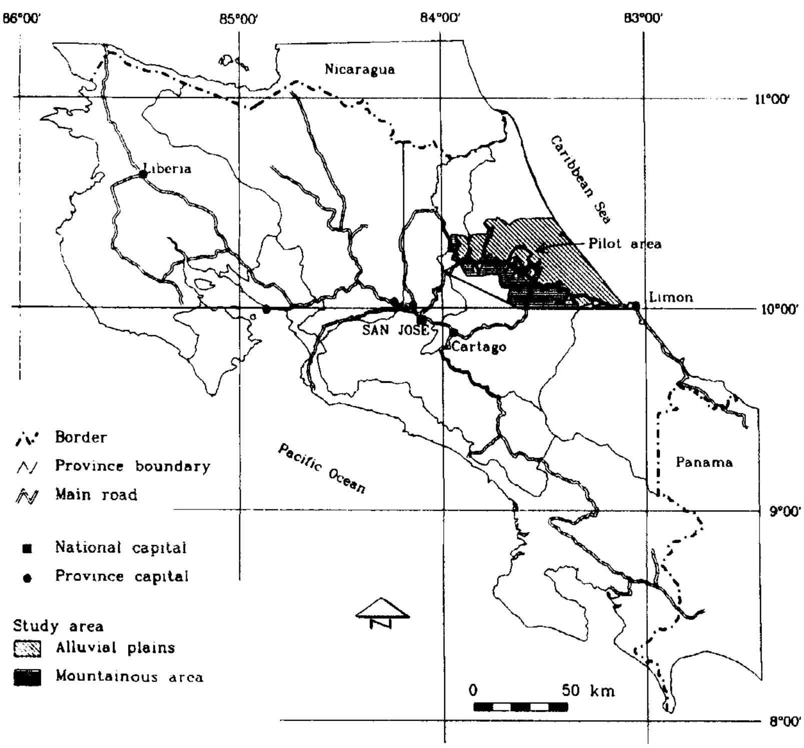

Figure 1. Location of the study area and the smaller pilot area

- Primary forest is converted into secondary forest and extensive agriculture. In the present context, extensive agriculture comprises patches of primary and secondary forest in combination with extensively managed pastures for cattle rearing accompanied by arable farming for home consumption (Sader and Joyce, 1988).
- After deforestation, the infrastructure is improved and an intensification (in terms of inputs per unit area and time) of agriculture takes place, coinciding with the cultivation of annuals and perennials as cash-crops.
- On fertile, well-drained soils, banana plantations are developed, some immediately after deforestation, but mostly as conversions from pastures. More recently other plantation crops such as ornamental plants and palm heart (*Bactris gasipaes*) have been introduced.

Although these land-use modifications are described in general terms in the literature, the process and the dynamics have never been quantified.

MATERIALS AND METHODS

The study area comprises 2942 km^2 for which aerial photographs taken in 1992 at a scale of 1:60 000 are available. Additionally, satellite imagery (Landsat TM) covering the northern Atlantic Zone is available. For a smaller pilot area of 151 km^2, aerial photographs are available at scales of 1:60 000 or even more detailed, taken at approximately 10-year intervals (1948, 1952, 1960, 1973, 1984, 1992). The 1948 and 1952 coverage of the pilot area is only partial. Therefore a combined interpretation was made, hereafter referred to as 1950. A photographic interpretation of the 1992 images has been made to identify land cover, and ground truthing has been carried out to verify those interpretations (Belder, 1994). The classification procedure developed for the 1992 photographs has been used to interpret the photographs of the pilot area for previous years. The interpretations are corrected geometrically to a single geographic basis. For the study area, a 1:150 000 reconnaissance soil survey was carried out by Wielemaker and Vogel (1993). Both the soil map and land-use maps are characterised by many complex mapping units representing combinations of different soils and land use. Owing to the scale of the original data, spatial seggregation of soil or land use is impossible. For soils, the dominant soil type in each of the mapping units is considered to be the driving force behind land-use changes. The land-use maps were generalized into five broad land-cover types: forest (F), extensive agriculture (Ex), pastures (Pa), mixed cropping (Mi) and plantations (PI). All data were processed using PC Arc/Info version 3.4.2.

Method 1: A single-time analysis of spatial patterns

When land-use data of only one collection data are available, which is often the case in developing countries, it is normally impossible to draw any conclusions on temporal dynamics. However, when qualitative knowledge on the colonization history is available, it may be combined with the land-use data to derive insight into the evolution of spatial patterns. In the study area, the distance between the main roads and the actual deforestation frontier is related to the date of colonization, and in particular to land-cover conversion from forest cover. Thus, all geographic positions in the area can be related to a certain stage in the land-use sequence, starting from the earliest, i.e. closest to the main roads. By interpreting the spatial pattern as a chronological sequence, land-use patterns in time may be deduced. However, this pattern may be modified by soil type and other physical parameters (e.g. altitude and slope). These modifications can be studied by stratifying the area on the basis of these parameters.

Calculation procedure

The study area comprises two main agro-ecological zones, a mountainous area in the south and large alluvial plains in the north (see Figure 1). The mountainous area includes the footslopes of the Cordillera de Talamanca and the Cordillera Central and the higher part of their alluvial fans. The plains include the lower part of the alluvial fans and the large alluvial plain, with remnants of older mud-flows and some Pleistocene volcanic cones. The main road, running parallel to the old railroad which was the

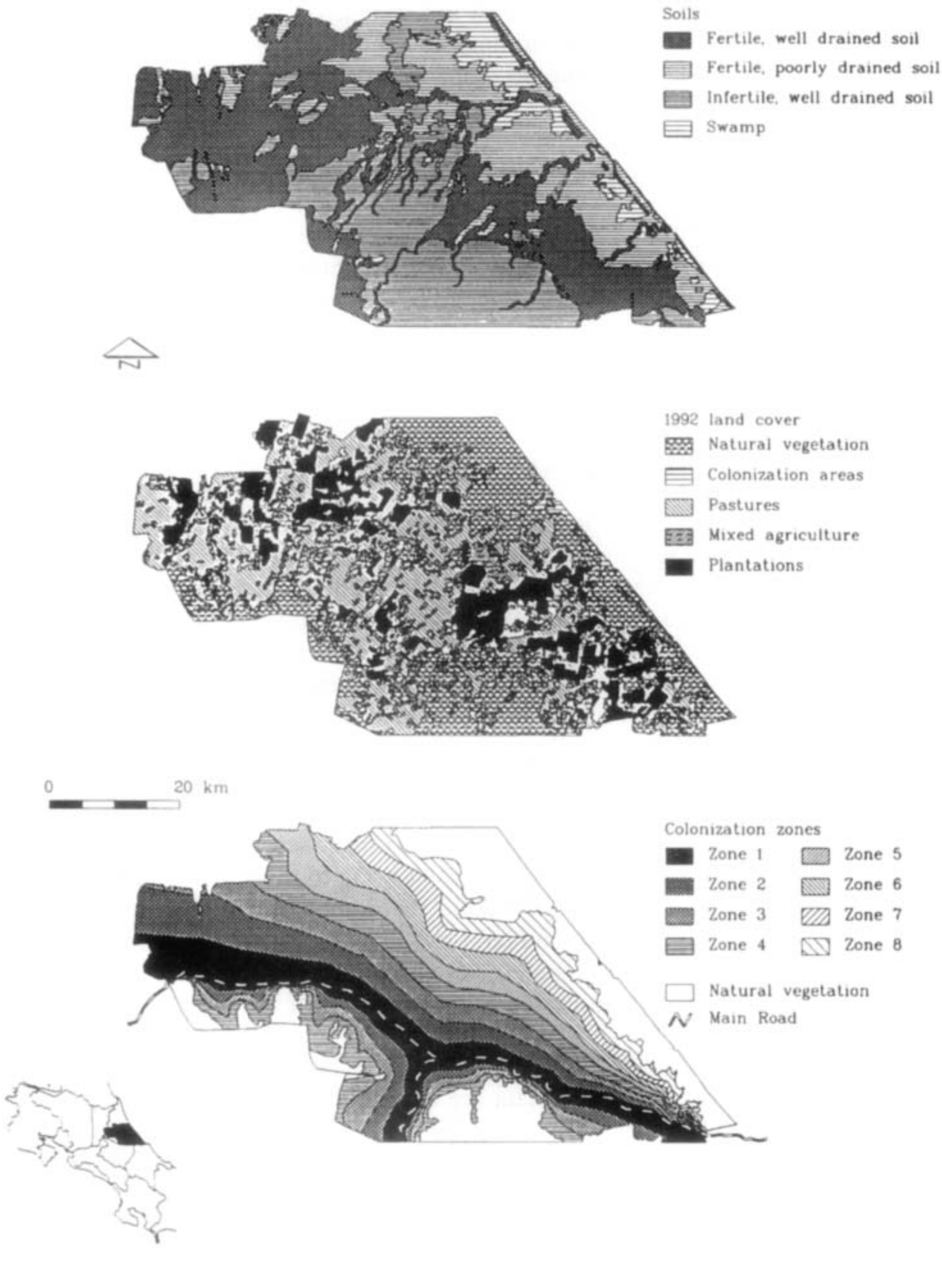

Figure 2. Soils, 1992 land cover, and colonization zones in the study area

starting point of the colonization of the Atlantic Zone, has been constructed along the junction of the two areas. The actual deforestation frontier in the north was identified on the 1992 aerial photographs. The northern part of the Atlantic Zone is not included in the study area owing to the lack of 1992 aerial photographs for that region. Nevertheless, the location of the deforestation frontier is necessary to determine the location of the colonization zones in the study area. The frontier was therefore identified on the basis of satellite imagery (1991 Landsat TM).

Assuming linearity in the colonization pattern between the railroad and the deforestation frontier, eight zones (N1 – N8) were identified between the main San José–Limon road and the actual colonization frontier in the alluvial plains (Figure 2). In the mountainous area south of this road, the colonization frontier is closer to the road and four zones (S1 – S4) were identified. Because the colonization zones are not equidistant around the road, the area between the road and the colonization frontier was subdivided into zones that were characterised by a specific ratio between the distance to the road and the distance to the colonization frontier. The colonization zones vary in width between 1.5 km in the east and 5 km in the west (where colonization took place more rapidly).

The soil map has been generalized into four main soil groups: (i) well-drained soils with a relatively high fertility; (ii) poorly drained soils with a relatively high fertility; (iii) well-drained soils with a relatively low fertility; (iv) the peat soils in the swamps. These soil groups can be classified according to soil taxonomy (Soil Survey Staff, 1992) as (i) Andic Eutropept and Typic Udivitrand; (ii) Aquandic Tropaquept; (iii) Oxic and Andic Humitropept; (iv) Histosols. The peat soils in the swamps were excluded from the analysis. In part the poorly drained soils are artificially drained and consequently similar to the fertile, well-drained soils.

The colonization zones were projected onto an overlay of the soil map and the land-use map, and consequently land use in each of the zones was determined.

Results

Figure 3 presents the percentage area coverage of the five broad land-cover types for three major soil groups as a function of the geographic position (colonization zones).

Fertile well-drained soils in the plains are rapidly deforested after colonization and the forest cover is replaced by extensive agriculture. Extensive agriculture is slowly replaced by plantations and pastures. In the mountainous areas deforestation seems to proceed at slower rates, probably because of the sloping landforms with related problems of accessibility. Coinciding with the deforestation, the area under plantations, mixed cropping and pastures slowly expands.

On the fertile, poorly drained soils, land-cover modifications are less pronounced. The importance of plantations on these soils is striking (up to 90 per cent on N3). Because deep artificial drainage is standard practice in the plantations, excess water is not a severe limitation. In addition, plantations require large continuous areas (at least 100 ha). The fertile well-drained soils are all developed and now hard to obtain, whereas the poorly drained soils are mostly under pasture and extensively used. In the southern mountainous areas fertile, poorly drained soils are almost absent and therefore not relevant.

Infertile, well-drained soils are dominated by extensive agriculture in recently colonized areas in the north (N5–N8) while pastures dominate in the older colonized areas (N1, N2). South of the road, in the mountainous areas, there is still considerable forest cover (almost 50 per cent of the area).

The results show that the temporal sequence of land-cover transformation and modification through human land use can be deduced from the actual spatial distribution in relation to the main roads and the deforestation frontier. Large differences are seen between the land-use sequences on the different soils, indicating the importance of such a stratification parameter.

Method 2: Standard Markov chains with a soil-type modifier

Land-use sequences or Markov chains (Cox and Miller, 1965) are based on calculation of the probability that one land cover changes into another. In the modified Markov approach, soil types are introduced to reflect the fact that, for biophysical reasons, land covers are closely linked to soil types (e.g. banana plantations occur only on fertile soils). A transition matrix may be established when the distribution of land use is known for more than 1 year. This transition matrix is used for the calculation of probabilities of Markov chains. At a detailed temporal scale the sequences correspond to land-cover modification or crop rotations (Jansen, 1994). At a coarser temporal scale the sequences correspond to land-cover conversions, such as the conversion of forest to pasture or arable lands, and to larger time lags between observations.

With relatively long time lags between observations, several land-use conversions can take place within one time lag. Two sequences that at first sight look different may well be the same when several modifications take place within one time lag. For example, the two sequences forest–pasture–mixed and

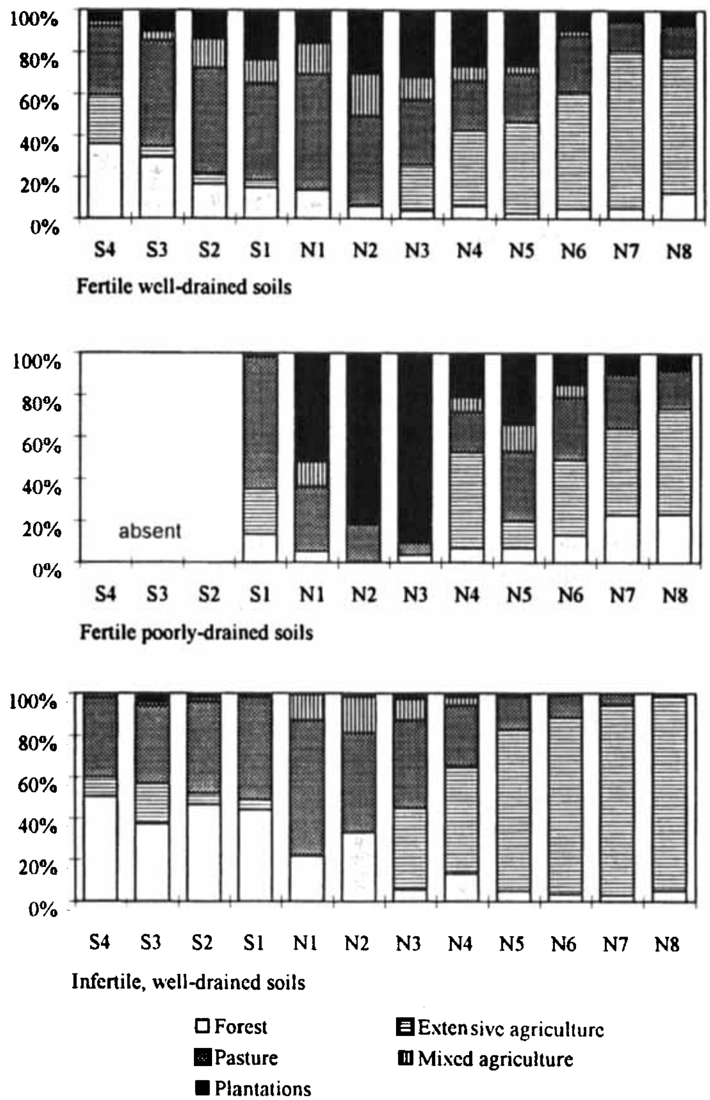

Figure 3. Land use per soil type and colonization zone

forest–extensive–mixed can be observed when the actual sequence is forest–extensive–pasture–mixed, and land-use modifations take place fast compared to the temporal resolution.

The analysis should be time-independent, i.e. sequences starting at different times should be treated similarly in the analysis. This means that the sequences F–F–Ex–Pa and F–Ex–Pa–Mi will be considered equal, as they only differ in the time that colonization started. For a single-step probability (with only two observations in time) this problem will not occur.

Calculation procedure

An overlay of the five land-use maps was produced resulting in land-use sequences for each of the newly created polygons. This results in a four-dimensional transition matrix where each cell corresponds to the total area of a certain land-use sequence. For the pilot area, the time lags were relatively large (approximately 10-year steps). Owing to the relatively small area, the sample of polygons is relatively small. In combination with the large number of possible combinations, almost each polygon yields a unique land-use sequence. Therefore, the four samples, representing the land-use modifications in each

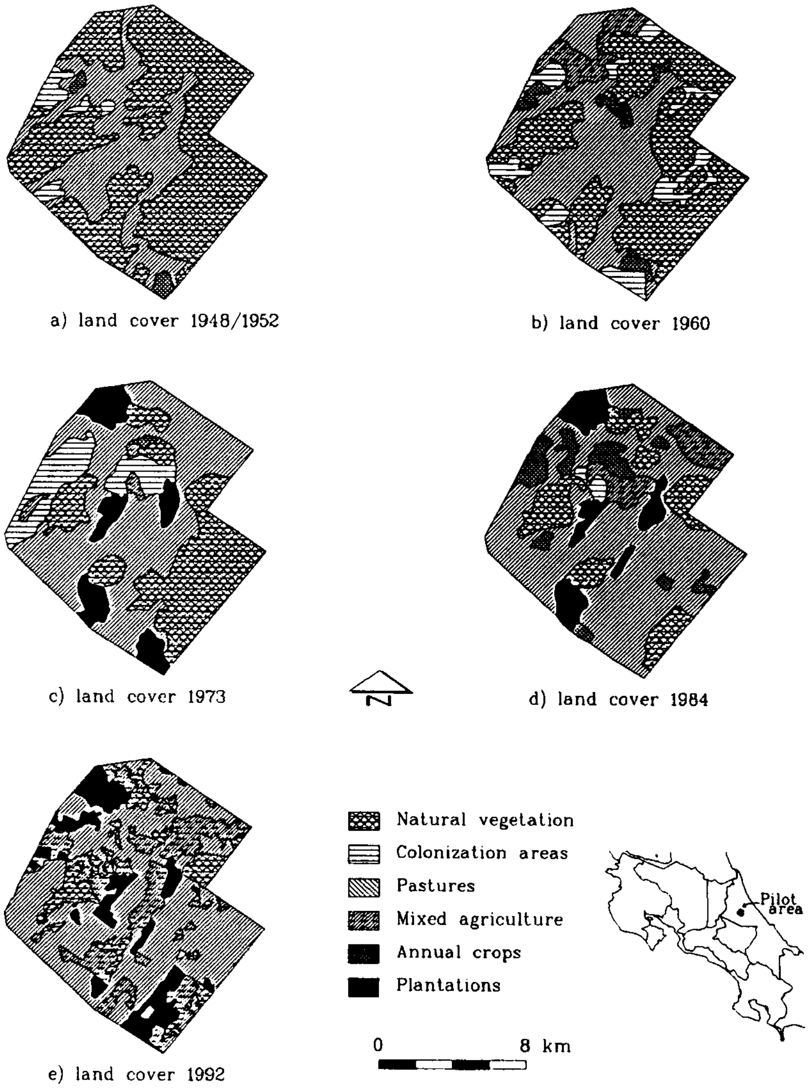

Figure 4. Land use in the pilot area between 1950 and 1992

of the time steps, have been combined yielding single-step Markov chains. As a result, the analysis is time-independent: differences between 1950 and 1960 are treated in a similar way to differences between 1960 and 1973. A soil-type modifier is included by projecting the overlay onto the soil map.

Results

Figure 4 presents the five land-cover maps for the study area. The single step Markov chains (see Table I) indicate the probabilities for land-cover conversions on each of the soil types. The probabilities on the diagonal indicate the probability that no land-cover modification takes place in a 10-year interval. Their generally low value, around 0.5, indicates that the area is highly dynamic. For example, it can be deduced that the area under forest may be reduced every decade, with that reduction being as high as 54 per cent on the fertile well-drained soils, rates that are comparable with the rates found by Sader and Joyce (1988) and Veldkamp, *et al.* (1992). In 1950 almost 50 per cent of the study area was under forest

Table I. Probabilities for land-cover changes in time steps of approximately 10 years per soil type (values of P: 0≤P≤1)

Soil	Fertile, well-drained					Fertile, poorly drained					Infertile, well-drained				
	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl
Forest	0·46	0·14	0·15	0·12	0·13	0·56	0·09	0·16	0·08	0·11	0·40	0·18	0·19	0·20	0·03
Extensive agriculture	0·11	0·47	0·08	0·15	0·19	0·12	0·43	0·09	0·18	0·18	0·10	0·34	0·38	0·16	0·02
Pasture	0·10	0·12	0·48	0·14	0·26	0·13	0·08	0·41	0·25	0·13	0·16	0·09	0·37	0·30	0·08
Mixed	0·04	0·03	0·20	0·50	0·24	0·06	0·04	0·19	0·38	0·33	0·07	0·04	0·20	0·67	0·02
Plantation	0·05	0·10	0·27	0·12	0·36	0·13	0·07	0·26	0·19	0·36	–	–	–	–	–

compared with 10 per cent in 1992. The fertile, poorly drained soils show the lowest deforestation rate, probably because of their low agricultural potential. As defined here, the forest cover includes both primary (logged) forest and secondary regrowth. This explains why conversions from other land covers into a forest cover occur: they imply conversions into secondary forest types.

Extensive agriculture is mostly converted into pastures and on fertile soils also into plantations. The area under a certain land cover does not influence the probabilities for land-cover change. For instance, extensive agriculture is almost absent on the fertile, poorly drained soils, significantly reducing the value and accuracy of the probability estimates for these soils. Only small differences occur between the soil types. Conversion of any of the land covers into plantations on the infertile, well-drained soils is unlikely. Generally, on the fertile, well-drained soil the probabilities of converting any of the land covers into mixed cropping or plantations is high, corresponding to the trends observed in the study area.

Method 3: Geo-referenced Markov chains

The sequences observed on the basis of the standard Markov chain analysis are refined by introducing probability modifiers based on geometric and geographic position. The geometric position reflects the size and shape of the polygon, as expressed by surface area and an index value for the shape of the polygon. Generally, land-cover conversion starts at the polygon margins (Skole and Tucker, 1993).

Calculation procedure

The calculation is based on four consecutive steps.

(1) In a manner similar to that for the standard markov chains, the different aerial photographs are interpreted and geometrically corrected.
(2) For each of the polygons the surface area and circumference are provided by the GIS package. Two additional parameters are calculated.

(i) An index value representing the shape of the polygon

$$S = 4\pi \frac{A}{C^2}$$

where S is the index for shape, A is the area of the polygon, and C is the circumference of the polygon.

The index value S is independent of size, and ranges from 1 for circular polygons to near 0 for extremely irregularly shaped polygons. Polygons along the border of the map are excluded from the analysis because their shape is unknown.

(ii) An index value for land cover in neighbouring polygons. The length of the boundaries between any polygon with each of its neighbours is available in the line attribute table in the GIS. Land covers are ranked according to management intensity and the observed conversion sequence (1) forest, (2) extensive agriculture, (3) pasture, (4) mixed farming, and (5) plantation. A boundary index N for the type of land use in neighbouring polygons is calculated by multiplying the fraction of the boundary with the corresponding rank number.

$$N = \sum_{Lu=1}^{5} f \times Lu$$

where N is the boundary index, f is the fraction of the border adjoining Lu, and Lu is the land-cover rank.

The index value N will range between 1 when the polygon is completely surrounded by forest to 5 when the polygon is surrounded by plantation. In other words, the boundary index indicates the weighed average ranked land cover of neighbouring polygons.

(3) An overlay is created for the five different land-cover maps.

(4) The land-use modification between t_i and t_{i+1} is calculated and stratified for size, shape and neighbour index. Depending on the size of the study area, and the number of observation dates and the number of polygons, the size, shape index and neighbour index can be stratified in a number of classes. Although the number of observation dates in the Costa Rican case-study is relatively high, the area for which the aerial photographs were available is small, especially when the outside polygons have to be excluded. For illustrative purposes the effects of the three different parameters are presented separately.

Results

The results are presented in the Table II. Separate stratifications were carried out for size, shape and neighbours of the polygons.

The size of the polygons is classified into three groups, each with an approximately equal number of observations. The size of the polygons significantly influences the land-cover modifications. This is clearly shown by the probability that conversion of forest will take place, which ranges from 0.57 for small polygons to 0.16 for the large polygons. Similar results can be observed for extensive agriculture, pasture and plantations.

Although the shape of a polygon theoretically influences the probabilities, the results do not clearly confirm this effect since only a slight positive relation can be observed. Disturbances by other parameters such as soil type and polygon size, for which a clear relation has been found, may confound the influence of shape. A combined analysis may be necessary, especially because there may be a relationship between shape, land cover and soil type. Long narrow irregular shapes may, for instance, correspond with riverline or swamp forest on poorly drained soils. The shape, cover and land use will be related to drainage patterns and relief.

As for the size and shape index, the boundary index has been classified into three groups with equal numbers of polygons, and as with the shape index, no clear relations can be found.

DISCUSSION AND CONCLUSIONS

Changes in land use and cover over time have been studied in three different ways. The merits and drawbacks of the three methods are detailed below.

- Single-time analysis. Its advantage is that land-use data for only one observation date are necessary to obtain results. A clear disadvantage is that it can only be used in colonization areas for which qualitative data on the colonization history are available. It is probably most suitable to deal with land-cover conversion rather than with land-cover modification such as intensification, e.g. the change to high-

Table II. Probabilities for land-cover changes stratified for polygon size, shape and neighbouring cover types (values of P: 0≤P≤1

	Size														
	< 2 km^2					2–5 km^2					> 5 km^2				
	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl
	0·43	0·12	0·21	0·13	0·11	0·56	0·11	0·13	0·13	0·07	0·84	0·11	0·04	0·01	0·00
Extensive agriculture	0·12	0·37	0·11	0·20	0·20	0·12	0·43	0·09	0·18	0·18	0·15	0·79	0·03	0·02	0·01
Pasture	0·12	0·08	0·43	0·26	0·11	0·13	0·08	0·41	0·25	0·13	0·02	0·13	0·79	0·03	0·03
Mixed	0·07	0·03	0·10	0·53	0·27	0·06	0·04	0·19	0·38	0·33	0·06	0·08	0·09	0·57	0·20
Plantation	0·17	0·00	0·36	0·10	0·37	0·13	0·07	0·26	0·19	0·36	0·00	0·00	0·02	0·02	0·96

	Shape[1]														
	< 0·33					0·33–0·66					> 0·66				
	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl
Forest	0·46	0·05	0·27	0·19	0·03	0·53	0·11	0·11	0·15	0·11	0·56	0·10	0·23	0·11	0·00
Extensive agriculture	0·20	0·44	0·12	0·09	0·15	0·12	0·43	0·09	0·18	0·18	0·12	0·47	0·08	0·15	0·18
Pasture	0·16	0·03	0·47	0·25	0·09	0·13	0·08	0·41	0·25	0·13	0·08	0·14	0·41	0·34	0·03
Mixed	0·05	0·16	0·09	0·31	0·39	0·06	0·04	0·19	0·38	0·33	0·03	0·02	0·13	0·46	0·36
Plantation	0·08	0·02	0·33	0·27	0·30	0·13	0·07	0·26	0·19	0·36	0·04	0·07	0·22	0·15	0·52

	Neighbouring cover types[2]														
	< 2·33					2·33–3·66					> 3·66				
	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl	F	Ex	Pa	Mi	Pl
Forest	0·40	0·10	0·15	0·22	0·13	0·34	0·12	0·24	0·14	0·16	0·37	0·12	0·24	0·14	0·13
Extensive agriculture	0·16	0·33	0·16	0·19	0·17	0·15	0·38	0·09	0·18	0·19	0·14	0·35	0·12	0·18	0·21
Pasture	0·14	0·17	0·34	0·21	0·14	0·21	0·15	0·28	0·25	0·10	0·11	0·15	0·41	0·23	0·10
Mixed	0·11	0·13	0·16	0·27	0·34	0·13	0·03	0·17	0·32	0·35	0·16	0·04	0·16	0·34	0·30
Plantation	0·20	0·13	0·17	0·16	0·34	0·20	0·08	0·21	0·23	0·28	0·14	0·06	0·26	0·18	0·36

[1] Shape is defined as an index value *S* (see text).
[2] Neighbouring cover types are calculated as an index value (*N*) based on a ranking of cover types and border length (see text).

yielding varieties and use of higher inputs, which are too detailed to be captured. In the single-time analysis, even when good insight into the colonization history does exist, supposed changes may actually involve different developments (or land-use sequences) at different locations in the same zone. Alternative approaches may be developed for other areas where clear spatial–temporal patterns of land use exist in relation to, for example, urbanisation, mining or tourist industry developments.

- Classical markov chains. When more than one land-use inventory is, or can be, carried out, Markov chains are an appropriate tool. The advantage over the singe-time analysis is that for each polygon land-cover changes are quantified in time. It is demonstrated that the inclusion of a soil modifier is an important improvement in the standard Markov chain approach.
- Adapted Markov chains. Indicators to differentiate Markov chains are developed by carrying out a spatial pattern analysis of the polygons themselves and the neighbouring polygons (border analysis). Combining the spatial pattern indicators with a stratification for soil type is possible, although it requires large datasets to have sufficient data for each class. In that case, the shape parameters should

be determined before the overlay is made with the soil survey. No conclusive evidence could be given that shape and neighbouring polygons are related to changes in probabilities of land-cover change, although this may be likely on practical grounds (e.g. Skole and Tucker 1993). This merits further study.

The quantification of land-use dynamics is essential in studies of land use and cover change to assess the impact on land degradation or the feedback to climate change models. This would improve the current approaches in land-use inventory studies that focus on spatial analysis but remain qualitative, and do not allow a comparison with other regions. There is an increasing need for statistical analysis to support, for example, observed differences in Markov chains or between maps. Recent reviews on this topic do not yield any statistical test for this kind of analysis (e.g. Bailey, 1994; Bonham-Carter, 1994).

The proposed indicators for the description of land-use dynamics can be determined with standard GIS packages, although for the adapted Markov chains a vector-based system is preferable.

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