GIS-based ecosystem fragmentation analysis: The Riviera Maya, Mexico, as a case study.

Engelberth Soto Estrada
Universidad Tecnologica Centroamericana, Tegucigalpa, Honduras, email: engelberth.soto@unitec.edu

ABSTRACT

This paper presents some results of a Geographic Information Systems (GIS)-based ecosystem fragmentation analysis, which was effectuated in the region known as the Riviera Maya in the south of Mexico. This investigation aimed to supervise the effect of the implementation of a land-use programme on environment in the Riviera Maya, from the point of view of fragmentation of ecosystems and habitats. The assessment was based on the remote sensing interpretation of two Landsat Geocover Mosaics (LGMs) of 1988 and 2001. LGMs were classified using a supervised multi-spectral classification method. To determine extent and pattern of fragmentation, six landscape indices were calculated and compared: (i) minimum, mean and maximum patch area; (ii) patch perimeter; (iii) the second shape index (S2); (iv) the fractal dimension index (D); (v) the Nearest Neighbour Distance (NND); and (vi) the Normalized Difference Vegetative Index (NDVI). Results showed that there was a reduction in the total area of habitat available and that fragmentation of vegetation increased in the Riviera Maya. Construction of transport infrastructures and clearing for urban and tourism development were the main mechanisms causing fragmentation.

Keywords: habitat fragmentation, remote sensing, landscape indices, Riviera Maya.

1. INTRODUCTION

The Riviera Maya is located in the State of Quintana Roo on the Caribbean coast of Mexico (see figure 1). It covers 182,000 ha between the parallels 20°20'24" and 21°10'48" of north latitude, and the meridians 86°44'24" and 87°28'12" of west longitude. The Riviera Maya is recognized by its biological diversity and cultural richness and, in the last decades, by the accelerated tourism development.

It has been estimated that 1,252 species of plants, 60 families of coral reef fish, 16 species of amphibians, 79 of reptiles, 340 species of birds, 43 of terrestrial mammals, 39 of flying mammals and 8 of marine mammals occur in Quintana Roo (CECADESU 2006:7). The Riviera Maya is considered to have a high ecological significance due to the existence of rare, vulnerable and endangered species. A minimum of 246 species of vertebrates are found in the ELUPP's area (INE 1999:2). In addition, there are several vestiges of the Maya culture along the coastal line, i.e. Tulum, Xel Há, and Xcaret. Currently, around 45,000 Maya speakers live in the region (CDI 2006)

Tourism represents more than 90 percent of the regional GDP (GQR 2000). In 2004, tourism in the Riviera Maya generated more than 4.3 billion United States dollars (USD), which corresponded approximately to thirty five percent of the Mexican tourism revenues (SEDETUR 2005).

The so-called Ecological Land-Use Planning Programme (ELUPP) Cancun-Tulum (see administrative boundaries in figure 1) was implemented in 1996 as a strategic instrument to integrate continuing growth with long-term sustainable development. Through the implementation of the programme, development (to reach 11 million tourists annually by 2025, representing USD 10 billion revenues per year; GQR 2000 and FONATUR 2004) and environmental protection goals (e.g. to promote sustainable development, to protect aquifer recharge areas, to implement urban growth thresholds, to minimize habitat fragmentation) should be achieved. However, until present no monitoring mechanism was used to determine how the implemented strategies have influenced regional development and thus what the consequences on the environment are.

This investigation aimed to supervise the effect of tourism development, promoted by the ELUPP Cancun-Tulum, on the environment in the Riviera Maya, from the point of view of fragmentation of ecosystems and habitats.

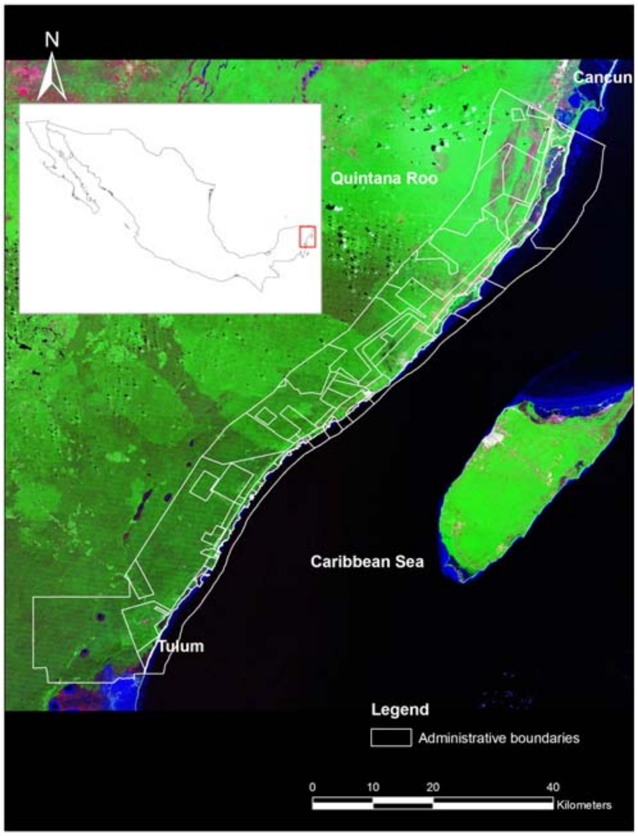

Figure 1: Location of Riviera Maya

2. METHODOLOGY

Habitat fragmentation is in a wider sense "a disruption of once large continuous block of habitat into less continuous habitat, primarily by human disturbances such as land clearing and conversion of vegetation from one type to another" (Franklin *et al.* 2002:20). Habitat is defined as the place or type of site where an organism or population naturally occurs (CBD 2006). In this study, to determine habitat fragmentation four questions were approached: (i) what is being fragmented? (ii) what is the scale of fragmentation? (iii) what is the extent and pattern of fragmentation? and (iv) what is the mechanism causing fragmentation? (Franklin *et al.* 2002:25-28).

To answer these questions, the first step was to build a GIS-database to manage digital information. Then, a supervised multi-spectral image classification method was used to classify LGMs (see figure 2). Three colour composites were created to support the training phase. Land-cover classes were determined according to a land-use map elaborated by the National Institute of Statistics, Geography and Data Processing of Mexico (INEGI 1997). The number of training samples was between 30 and 50 per land-cover class. However, due to the lack of information, this analysis was carried out to the programme's north part (94,190 ha; see figure 2).

Finally, in order to determine extent and pattern of fragmentation, six landscape indices were calculated and compared, using the 1988 and 2001 classified LGMs: (i) minimum, mean and maximum patch area; (ii) patch perimeter; (iii) the second patch index (S2), (iv) the fractal dimension index (D); (v) the Nearest Neighbour Distance (NND); and (vi) the Normalized Difference Vegetative Index (NDVI).

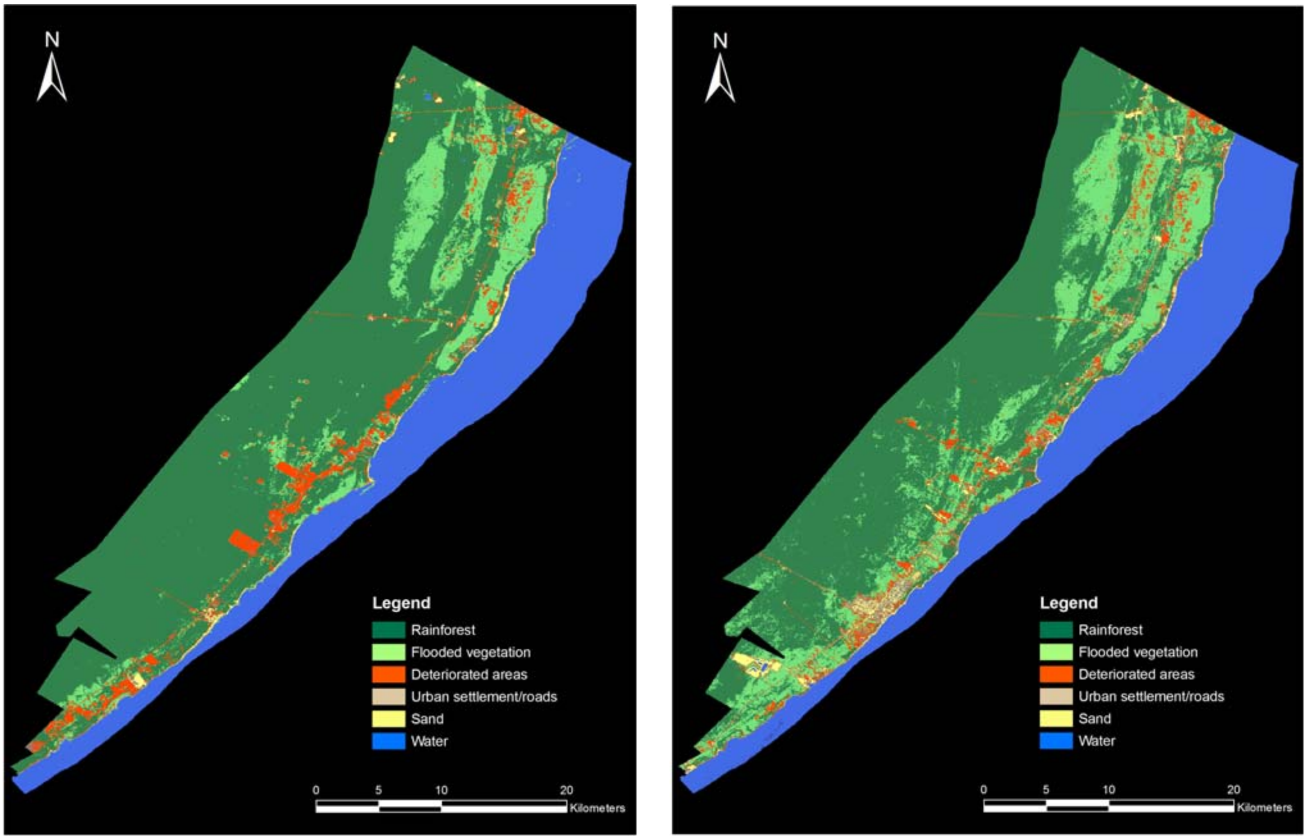

Figure 2: Digital image classification 1988 and 2001, respectively, according to the Minimum Distance-to-mean classifier

3. RESULTS

3.1 WHAT IS BEING FRAGMENTED?

There is a lack of adequate knowledge to date about habitat distribution in the Riviera Maya. It is possible to mention, in a very general way, that the main habitats being fragmented are medium and low rainforest, coastal-dune vegetation, and flooded vegetation (rainforest/palm groves, mangroves). These plant societies were supposed in this research (due to their extension) to hold most of the species in the Cancun-Tulum region.

3.2 WHAT IS THE SCALE OF FRAGMENTATION?

The analysis presented here approached fragmentation of vegetation at regional level. The assessment scale may be considered as wide-range (fragmentation at wide-range scale can affect dispersal between populations; Franklin et al 2002:25), since it was assumed that most of the Riviera Maya's species occur in the habitats mentioned above. However, there is not enough information to determine the response of species, populations and individuals to fragmentation at this scale. This assessment can be at wide-range for some species, and at population level or home-range for others.

3.3 WHAT IS THE EXTENT AND PATTERN OF FRAGMENTATION?

Extent of habitat fragmentation is the degree to which fragmentation has taken place within a specified spatial scale, whereas the pattern of fragmentation describes patch geometry, including size, shape, distribution and configuration. The results of the calculated landscape indices are presented below.

3.3.1 MINIMUM, MEAN AND MAXIMUM PATCH AREA

In this analysis, 71,828 ha of terrestrial habitat were evaluated (see figure 2). Rainforest and flooded vegetation (the main vegetation communities) covered 66,990 ha in 1988 and 64,996 ha in 2001, which represented 93 and 90 percent of the terrestrial area, respectively. The number of patches (defined as those polygons shaped between roads, electric lines, deteriorated and urban areas) increased and consequently their individual size decreased (see table 1). Map 3 illustrates patch size distribution.

Table 1: Patch size of vegetation in the Riviera Maya (1988-2001)

Year	Number of patches	Area (ha)			
		Minimum	Mean	Maximum	Total
1988	76	0.06	881	33,483	66,990
2001	100	2.50	649	13,652	64,996

During the period 1988-2001, the number of patches grew by 31 percent, whereas their mean size decreased from 881 to 649 ha (-26 percent). In the same period, the maximum polygon size decreased by 59 percent, from 33,483 to 13,652 ha.

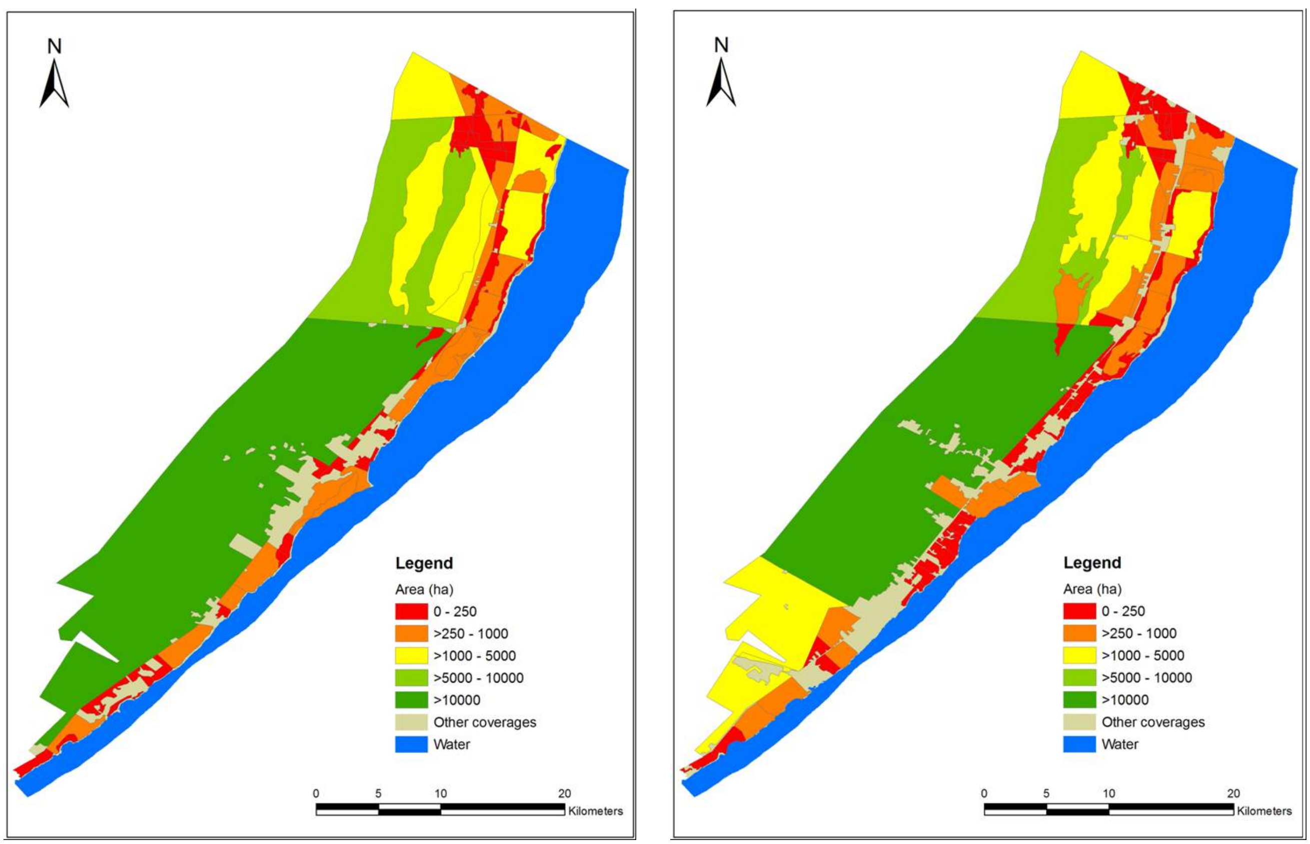

Figure 3: Patch size distribution 1988 and 2001

3.3.2 PATCH PERIMETER

Patch perimeter is included in table 2. Results showed that during the analysis period remnant edges grew from 945 to 1,072 km (13 percent), while the mean value decreased by 14 percent.

Table 2: Patch perimeter in the Riviera Maya (1988-2001)

Year	Number of patches	Perimeter (km)			
		Minimum	Mean	Maximum	Total
1988	76	0.16	12.43	167.97	945.20
2001	100	0.76	10.72	101.73	1,072.69

3.3.3 SECOND SHAPE INDEX (S2)

The second shape index was calculated as:

$$S2 = l/2\sqrt{(a*\pi)}$$

; where l is the perimeter and a the area of each patch. S2 has values >0 without limit, the bigger the S2 value, the more complex the shape of the patch. Table 3 shows the values of the second patch index.

Table 3: Second shape index (S2) in the Riviera Maya (1988-2001)

Year	Second shape index
1988	1.7247
2001	1.6461

3.3.4 FRACTAL DIMENSION INDEX (D)

Fractal dimension is a measure of patch shape complexity. Fractal dimension was calculated as (CBMAS 2006; Kenkel & Walker 2006; McGarigal et al. 2002):

$$Di = 2\ [\ln(Pi/4)/\ln(Ai)]$$

were Ai and Pi are the area and perimeter of the ith patch, respectively. The average fractal dimension (Dm) is finally calculated as:

$$Dm = \sum Di/N$$

The fractal dimension equation generates values between 1 and 2. Fractal dimension approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters (McGarigal et al. 2002). In this assessment, the mean fractal dimension (Dm) was estimated 1.1973 in 1988 and 1.1143 in 2001.

3.3.5 NEAREST-NEIGHBOUR DISTANCE (NND)

Nearest-neighbour distance (NND) equals the distance in meters to the nearest neighbouring patch of the same type, based on shortest edge-to-edge distance. Nearest-neighbour distance has been used extensively to quantify patch isolation. According to the results obtained, in 1988 the mean NND value was 1,470 meters, whereas it was estimated in 362 meters in 2001.

3.3.6 NORMALIZED DIFFERENCE VEGETATIVE INDEX (NDVI)

The Normalized Difference Vegetative Index (NDVI) provides an estimation of health vegetation. NDVI was calculated as the ratio between the difference and sum of two spectral bands. One band is in the visible electromagnetic spectrum (red) and one band in the Near IR (infrared). NDVI is (NIR-Visible)/(NIR+Visible) (CBMAS 2006).

The NDVI equation produces values in the range of -1.0 to 1.0, where vegetated areas will typically have values greater than zero and negative values indicate non-vegetated surface features such as water, barren, ice, snow, or clouds (CBMAS 2006). The calculated NDVI values are illustrated in figure 4. In 1988 the average NDVI was 0.4721, and 0.1957 in 2001.

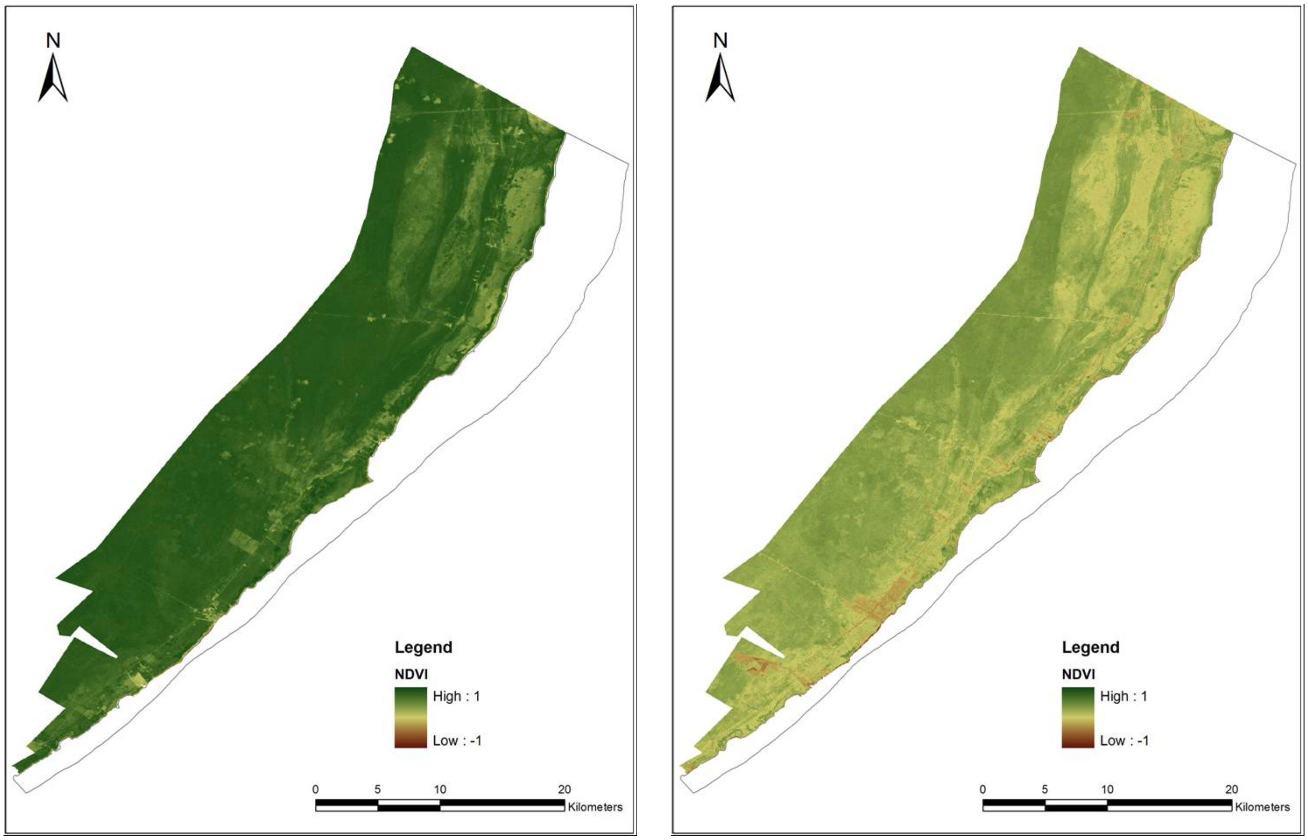

Figure 4: Normalized Difference Vegetative Index (NDVI), April 1988 and 2001

3.3.7 DISCUSSION

Patch extent affects the potential size of populations. Generally, the larger the remnant, the more likely it is that populations will be large and more likely to resist chance extinctions (Gilpin & Soule 1986). Human activities in the Riviera Maya resulted in a reduction of remnant size, which is a negative impact on both flora and fauna.

The total perimeter of patches increased during the analysis period, which might be interpreted as a negative environmental impact. Experience has shown that the effects of fragmentation are bigger at the edge of remnants, which can ultimately affect larger fauna both directly and indirectly through altering resource availability.

The average values of the second shape index (S2) and the fractal dimension index (D) suggested that, in general, patch shape has changed from irregular forms to forms predominantly square. The construction of linear structures (such as roads and electric lines) and urban settlements are the main causes of simplification of shape complexity in the Riviera Maya.

The nearest-neighbour distance (NND) average value decreased from 1998 to 2001. NND was based on the shortest edge-to-edge distance, calculated from cell centre to cell centre. A reduction in the NND may indicate that the patches are getting closer. In this case, however, it indicates that the vegetation remnants are being fragmented. This phenomenon can be explained as follows.

Imagine that there are 2 patches, let's say, 2,000 m away from each other. The construction of a new road (30 meters wide) divide one of them and now we have three remnants, two sharing a NND of 2,030 m (considering the original distance and the cell size), and two with a NND of 60 m (30 m road and 30 m cell size). It is easy to realize that the construction of new roads, which is in fact occurring in the Riviera Maya, will guide to a reduction in the NND average value. In our imaginary example, the average NND value decreased from 2,000 m to 1,045 m.

The Normalized Difference Vegetative Index (NDVI) 1988 and 2001 values indicated that vegetation density decreased considerably in the Riviera Maya. It may be caused by the human activities in the region, however, possible causes for lower than normal NDVI are also lack of precipitation or exceptionally cold temperatures (which can delay or cut short the growing season) and clouds (NASA Earth Observatory 2006). Nevertheless, no historical data on precipitation or temperature could be found to confirm or discard this possibility.

3.4 WHAT IS THE MECHANISM CAUSING FRAGMENTATION?

Mechanisms causing fragmentation can be natural (for example fire, wind, water, etc.) or anthropogenic (logging, agriculture, urbanization, etc). In a given area at a given scale, these mechanisms can simultaneously fragment habitat for some species while creating habitat for others (Forman 1997:413). In conservation issues, the mechanisms causing habitat fragmentation are often of primary concern, especially when these mechanisms are human-induced (Franklin et al. 2002:27).

Construction of transport infrastructures, and clearing for urban and tourism development are the main mechanisms causing fragmentation in the Riviera Maya. Road network grew by 61 percent, reaching 281 kilometres in 2001. During the period 1988-2001, urban and tourism areas grew by 616 percent. In addition, deteriorated areas increased by 30 percent, from 4,007 ha to 5,220 ha.

4. CONCLUSIONS

The analysis presented here demonstrated that there was a reduction in the total area of habitat available and that fragmentation of vegetation increased in the Riviera Maya. Construction of transport infrastructures and clearing for urban and tourism development are the main mechanisms causing fragmentation.

It was not possible to conclude, however, that fragmentation of vegetation is leading (or has led) to habitat fragmentation (because to date there is no information on habitat distribution in the Riviera Maya), and in such a case, which species are being affected.

Gascon *et al.* (2003:37) mentioned that not all the cases of fragmentation of vegetation have led to a decline in species richness after isolation. On the contrary, some taxonomic groups (such as mammals and amphibians) have shown an increase in species richness due to the appearance of open-area associated species. However, this author also pointed out that in Central Amazonia "regardless of whether a particular taxonomic group showed an increase or decrease in species richness after isolation, larger remnants maintained more species than smaller ones". Thus, a reduction in species richness as a result of the reduction in the total area of habitat available in the Riviera Maya might be expected.

Results suggest, in addition, that the ELUPP Cancun-Tulum has neither mitigated fragmentation in the Riviera Maya nor controlled anthropogenic activities.

Figure 3 showed that fragmentation (considering the distribution of patch size) and deterioration of vegetation (taking into account the distribution of NDVI values) were not influenced by the management schemes implemented through the ELUP-Programme. On the contrary, fragmentation and deterioration of vegetation took place along roads, affecting principally the area between the Federal Highway 307 and the coastal line. In fact, the areas designated as landscape protected areas (which are located near the coast) were the areas most affected by fragmentation and deterioration of vegetation.

The above mentioned may be caused by the inadequate implementation of the programme's strategies. Nevertheless, it is also questionable that the ELUPP Cancun-Tulum's requirements can ultimately lead to the mitigation of fragmentation. So far, the ecological criteria designed to mitigate fragmentation have been formulated at project level. In addition, there is a lack of environmental objectives at strategic level to specify the minimum area of habitats that have to be preserved, and the connectivity areas (corridors) required between those habitats.

4.1 FUTURE WORK

The analysis of habitat fragmentation requires a better knowledge on the distribution of species and communities in the Riviera Maya, and the relations between components of the landscape. To determine a more accurate habitat fragmentation assessment it will be necessary: (i) to determine species-specific habitat distribution for the entire Cancun-Tulum region; and (ii) to evaluate additional datasets (satellite images) according to the requirements of landscape indices.

In order to determine a detailed vegetation health pattern of change, for example, it has been recommended (NASA Earth Observatory 2006) to compare the average NDVI for a particular month of a given year with the average NDVI for the same month over the last 20 years, which is called NDVI anomaly.

In addition, it is necessary to determine clear environmental objectives concerning habitat fragmentation, i.e. the minimum critical size that the habitats need to be to preserve their characteristics species diversity and species composition (Lovejoy & Oren 1981), habitat connectivity (corridors needed), land consumption rates (by urban/tourism, transport network and mining), and monitor targets against which the effectiveness of implemented strategies can be tested.

Finally, in the case of urban and tourism development, additional information is required (e.g. satellite images with higher resolution, cadastral data) to determine adequately the extent of formal and informal settlements in the Riviera Maya.

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