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TROPICAL ALLUVIAL FOREST FRAGMENTATION IN THE EASTERN LOWLANDS OF COLOMBIA (1939–1997)

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ABSTRACT

Alluvial forests are under high pressure from human activities because of their value as agricultural, wildlife, timber and recreational land. Despite this, spatial patterns of alluvial forest deforestation are not well known. We studied forest alterations in a 2800 ha alluvial ecosystem using aerial photographs. During the study period (1939–1997), forests with canopy heights greater than 15 m (high canopy mature forest; HCM forest) decreased by 70·4 per cent while forests with canopy heights less than 15 m (low canopy mature forest; LCM forest) forests decreased by 51 per cent, producing a highly fragmented landscape. Factors responsible for forest change included human activities and river dynamics. Although most of the deforestation was related to human disturbance, almost 27 per cent of forest losses were due to channel migration of the Meta River. HCM forests were the most affected land cover since they are easily accessed, viable for logging and occurred on fertile soils, which are valuable for agriculture. LCM forests were less affected since their soil fertilities and inundation regimes were unfavourable to human uses, and thus, less prone to anthropogenic disturbances. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: tropical alluvial forests; deforestation; eastern lowlands; Meta River; Colombia

INTRODUCTION

Globally, research on deforestation has grown substantially during the last 10 yr, due to a greater recognition of the effects of forest loss and fragmentation on biodiversity and climate change. Despite increased research, the spatial patterns and impacts of deforestation are still poorly understood in some temperate regions, and practically unknown for many tropical regions, especially at a fine spatial scale. (Laurance, 1999; Geist and Lambin, 2001; Hobson *et al*., 2002). The interaction between ecological and anthropogenic factors is also not well understood, even though such information is crucial for management and restoration efforts (Dale *et al*., 1993; Turner *et al*., 1996; Hobson *et al*., 2002).

While the spatial patterns of deforestation are poorly understood for most tropical forest types, this is particularly true for alluvial forest ecosystems (Kvist and Nebel, 2001). Alluvial systems are often under tremendous pressure from human activities, since floodplains are not only highly valued for agricultural, wildlife, timber and recreation uses but also easily accessed (Clawson *et al*., 2001; Zarin *et al*., 2001). Alluvial forests are distinctly different from dry land forest types because they are established on fresh sediments from floods, which are exposed to seasonal

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fluctuations of overland flows and ground water levels, resulting in a few specific soil types. In contrast, dry land forests generally have a greater diversity of soil types and fertilities (Hiraoka, 1985; De Jong *et al*., 2001). Rivers and their alluvial landscapes are dynamic both in space and time, due to fluctuating hydrologic, geomorphologic and biologic processes. These processes are the result of spatial relationships with neighbouring aquatic, semi–aquatic and terrestrial ecosystems, which should be taken into account in the study and management of alluvial forests (Decamps and Naiman, 1989; Kvist and Nebel, 2001).

Fragmentation can negatively impact native plant species due to geographic isolation and decreased probabilities of re-colonization (Forman and Gordon, 1986; Farina, 1998). In fragmented tropical forest patches, edge effects appear to be a major cause of changes in plant communities. Recently, isolated fragments often show a reduction in species richness after excision from contiguous forest, and small fragments often have fewer species than large fragments or areas of contiguous forest (Turner, 1996; Laurance *et al*., 1998). However, the effects of fragmentation on alluvial forests can vary substantially from dry-land forests, because of their highly dynamic geomorphologic environment (Salo *et al*., 1986), resulting in high channel migration, and therefore, large tracts of exposed riparian forest edges.

In the eastern plains of the Orinoco and Amazon regions of Colombia, alluvial and gallery forests cover some 8·7 million ha, of which 3·5 million (40 per cent) correspond to high fertility floodplains of river originating in the Andes (Etter, 1998a,b). These forests have increasingly become subject to human use. In this paper, we examine how deforestation rates, fragmentation patterns and soil types affect an alluvial floodplain landscape of the Meta River in the Orinoco region. Specifically, we focused on the effects of river dynamics and human activities on forest turnover rates.

STUDY AREA

The study area is a 2800 ha mosaic of alluvial forest located along the Meta River (Department of Meta, Colombia), between 4° 07′ 33·46228″ and 4° 08′ 42·45623″ north latitude and 72° 55′ 03·77927″ and 72° 56′ 15·88119″ west longitude.

Inter-annual climate follows a mono-modal tropical seasonal pattern, with total annual rainfall of 2600 mm and an average annual temperature of 26°C. Mean monthly rainfall averages 300 mm during the wet season (May–October) and 52 mm during the dry season (December–March) (Fajardo, 1998).

Alluvial floodplains dominate the geomorphology of the study area. Although annual flooding occurs frequently over 5–7 months of the year at lower elevations, at higher elevations, flooding is sporadic and infrequent. The soils originate from fresh, quaternary sediments washed from the Andean cordillera. Three main soil composition types can be found in the alluvial plain (IGAC Instituto geogrÃfico AgustÚn Codazi, 1978; ORAM, 1998)

- **Pla:** Aquic Tropopsamments 60 per cent, Tropic Aeric Fluvaquents 20 per cent, Aquic Tropofluvents 15 per cent, Fluventic Tropaquents 5 per cent.
- **RAa:** Tropofluvents 65 per cent, Tropic Fluvaquents 35 per cent.
- **CPa:** Aquic Oxic Dystropepts 60 per cent, Fluventic Tropaquepts 40 per cent.

The natural vegetation of the area consists of forest mosaics surrounded by seasonal rainforests and savannas. Currently, only a small portion of the original old growth forests remains, with agricultural land cover fragmenting the landscape. We used dominant taxa to classify plant communities into four types (Madriñán, 2001):

- High Canopy Mature (HCM) forest (15–25 m): *Licania heteromorpha, Miconia multispicata, Phoebe cinamonnifolia, Cecropia obtusifolia* and *Ceiba petrandra*.
- Low Canopy Mature (LCM) forest (8–15 m): *Licania heteromorpha, Pithecellobium glomeratum and Cecropia obtusifolia.*
- Young forest (1–5 m): *Heliconia wagneriana, Cecropia obtusifolia, Bauhinia* sp., *Socratea exorrhiza* and *Theobroma cacao*.

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– Herbaceous and shrubby vegetation: *Paspalum fasciculatum, Gynerium sagittatum* and *Heliconia wagneriana*.

METHODS

Physical and biological components were used in an ecological mapping approach based on Kuchler and Zonneveld (1988). This methodology uses ground control points (Trimble GPS Pathfinder Pro XR/XRS®), ortho-rectified aerial photographs, existent cartographic maps (1:50 000 soil and 1:25 000 land use), visual photo-interpretation and Geographic Information Systems (GIS) to create digital land use\land cover (LULC) maps.

Mapping and Databases

Five stereoscopic pairs of black and white aerial photographs were used to delineate land cover units based on LULC. Photographs came from a range of years (1939, 1950, 1985, 1989 and 1997) and scales (1:25·000–1:40·000). A total of 13 LULC types were identified and grouped in two geomorphologic units:

Alluvial Plains:

– HCM Forest: Forests with canopy heights between 15 and 25 m.
– LCM Forest: Forests with canopy height between 8 and 15 m.
– Young forest with Shrubs: Forest with abandoned clear cuts and native shrubs.
– Young forest with grass: Corresponding to active clear cuts within forests.
– Cleared land.
– Water (Meta River).

Highland plains:

– Savanna: Natural grasses of highland plains.
– High plain gallery Forests (HPG): Small forest associated to high lands.

Temporal Analysis

We examined changes in LULC between four sets of consecutive periods (1939–1950; 1950–1985; 1985–1989; 1989–1997), by generating a matrix of change (Arcview 3·1®, Map Maker Popular 1999®). This method facilitates comparisons of temporal variation and succession paths of land cover types.

Fragmentation Indexes

We calculated the total forest proportion (TFP) to provide a basic assessment of forest cover in the region. TFP has been used as an index of forest fragmentation by other studies (Vogelmann, 1995; Wickham *et al*., 1999).

$$\mathrm{TFP} = \frac{\text{Total forest area}}{\text{Total non-water area}}$$

We calculated average forest patch size as simply the sum of the area of all forest patches divided by the number of patches.

Finally, we calculated the connectivity of the landscape in relation to the patch size (RSi). This is an index of forest connectivity that measures the relationship between the area of the largest forest patch and the total area of the same forest type. The formula for connectivity is:

$$\mathrm{RSi} = \frac{LC\ \text{forest}}{A\ \text{forest}}$$

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Where *LC forest* is the area of the largest forest patch and *A forest* is the total area of that particular forest type in the watershed.

Deforestation Rates

Total area was used to calculate deforestation rates for each LULC type (Dirzo and Garcia, 1990):

$$r = 1 - \left(1 - \frac{A_1 - A_2}{A_1}\right)^{1/t}$$

where $\boldsymbol{A_1}$ is the forest area at the beginning of the period, $\boldsymbol{A_2}$ the forest area at the end of the period and $\boldsymbol{t}$ is equal to the number of years for a given period.

Soils and Deforestation

We compared temporal and spatial differences in the percentage of each soil type covered by a given LULC. Percentage of each soil type covered by a specific plant community type was determined by merging existing maps of LULC, vegetation sampling and soil map layers (IGAC Instituto geogrÃfico AgustÚn Codazi, 1978), using GIS (Arcview 3·1®). Temporal changes were analysed over 58 yr using the four previously described data sets.

RESULTS

Temporal Changes by Vegetation Type

Over the course of the 58 yr examined in this paper, forest area declined by 71·5 per cent with the main deforestation events occurring before 1985 (Table I). HCM forest (A1) had the greatest reduction in area, losing 70·4 per cent (1100 ha) of its original coverage (Figure 1). In contrast, area coverage of LCM forest (A2) was reduced from 375 ha in 1939 to 184 ha in 1997, a 51 per cent loss in land cover (Figure 1).

Mean patch size of HCM forests declined from 128·9 ha in 1939 to 22 ha in 1997, while the mean patch size of LCM forests declined from 26·1 ha in 1939 to 14·9 ha in 1997 (Table II).

Finally, we found that cleared land covers (grasslands and agriculture) were inversely related to forest loss. Grassland and agriculture increased after deforestation by 631 per cent and 908 per cent, respectively.

However, after analysing the temporal changes in LULC patterns, the losses in alluvial forest cover are not only the result of anthropogenic land clearing but also due to river channel dynamics (Figure 2). The greatest forest loss occurred between 1950 and 1985, and for that period, anthropogenic sources were responsible for most of it. However, between 1939 and 1950, and 1985 and 1989, channel migration resulted in nearly as much forest loss as from human activities (Figure 4).

Annual Deforestation Rates

Although the total loss of forest area due to the combined impacts of anthropogenic and river activities has declined for all periods since 1950, for the three time periods between 1939 and 1989, annual deforestation rates increased. Annual deforestation rate was 1·6 per cent during the first and second periods, while between 1985 and 1989, rates peaked at 3·42 per cent, of which 1·14 per cent was caused by channel migration. After 1989, deforestation rates

Table I. Land cover changes within time periods (in hectares)

	1939–1950	1950–1985	1985–1989	1989–1997
HCM to cleared land	309·2	751·7	108·1	87·8
HCM to LCM	69·9	67·4	17·6	59·8
LCM to cleared land	50·8	67·5	69·0	33·5
LCM to HCM	110·2	47·9	25·7	142·1

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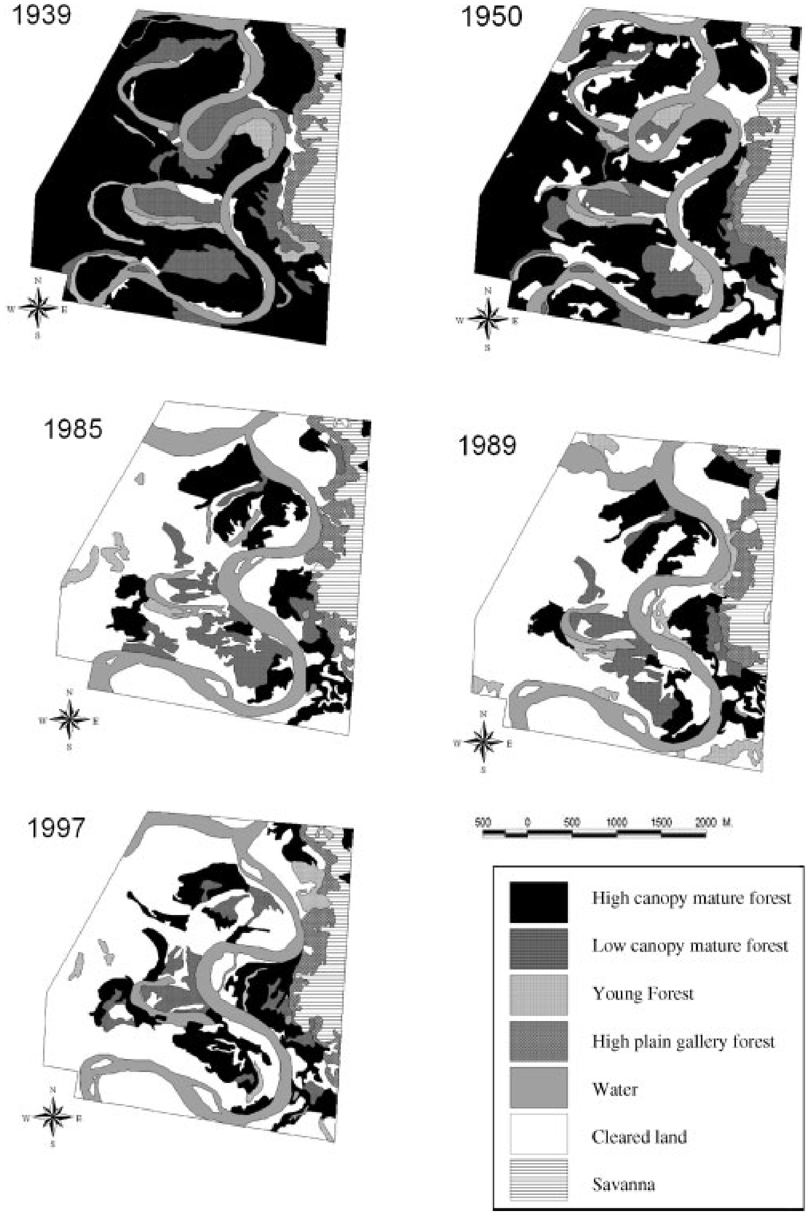

Figure 1. Temporal land cover maps highlighting HCM, LCM, young and HPG forest

decreased to 1·78 per cent (Table III), and in some areas, we observed forest regeneration and an increase in forest cover.

Fragmentation Index

Although the deforestation rate has decreased, system fragmentation has increased. The TFP has declined consistently from 0·29 in 1985 to 0·24 in 1989 and to 0·22 in 1997. At the same time, forest connectivity relative to patch size has declined from 0·45 in 1985 to 0·39 in 1989 and later to 0·25 in 1997 (Table II). This is principally

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Table II. Fragmentation indexes

	1939	1950	1985	1989	1997
Total forest cover (ha)	1835·2	1500·9	658·5	568·3	487·3
Largest fragment (ha)	937·1	686·0	299·4	222·5	122·0
Total forest proportion	0·82	0·66	0·29	0·24	0·22
Average patch size	128·9	72·9	32·4	42·2	22·0
Use number of patches	13	15	19	14	23
Connectivity (relative patch size, *RSi*)	0·51	0·46	0·45	0·39	0·25

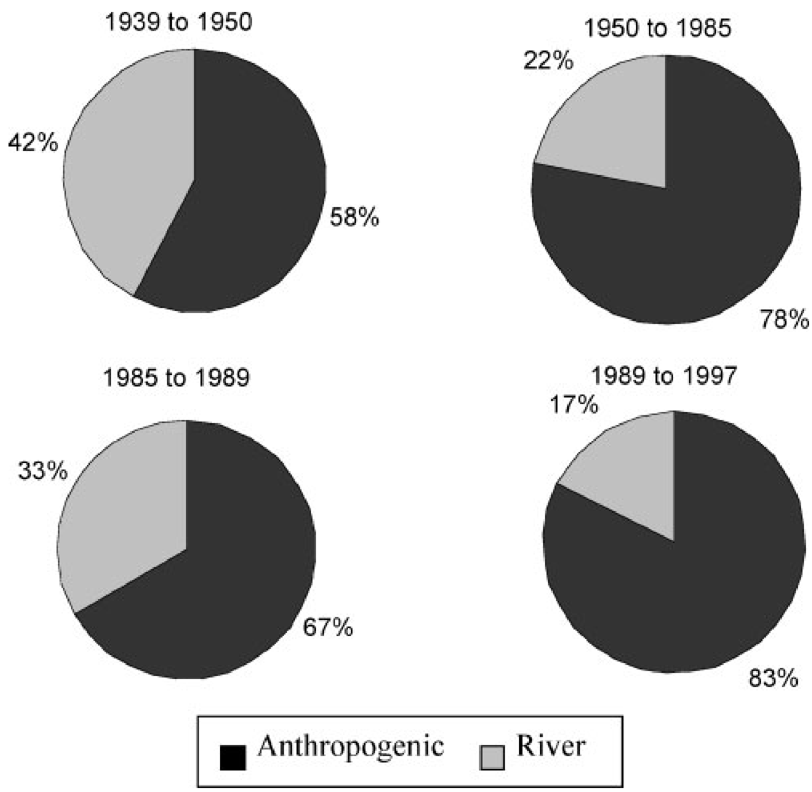

Figure 2. Forest loss due to anthropogenic activities and to river dynamics

because of a reduction in average patch size from 42·2 ha in 1989 to 22 ha in 1997 and an increase in the number of forest fragments from 14 in 1989 to 23 in 1997.

Soils and Deforestation

Comparing soil maps with our LULC maps, we found a positive relationship between forest persistence and PLa (young coarse and moderately coarse alluviums), a soil type, which is inundated between 5 and 7 months per year. In contrast, we found a negative relationship between forest persistence and CPa (mature coarse and moderately

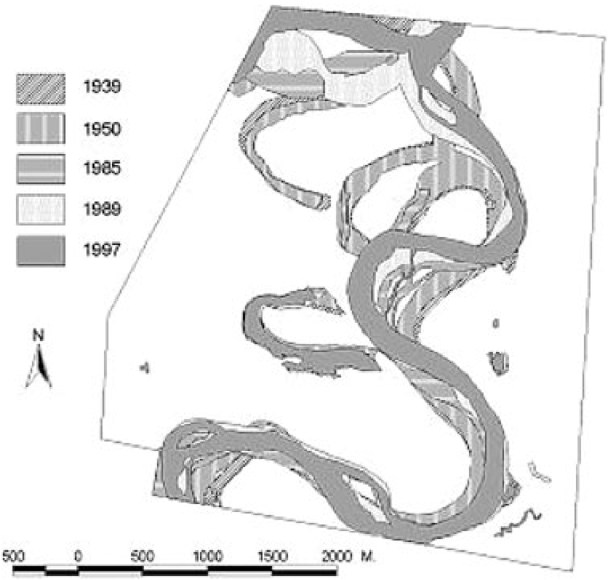

Figure 3. Changes in the Meta River channel during the 1939–1997 period, as evidenced from the aerial photographs

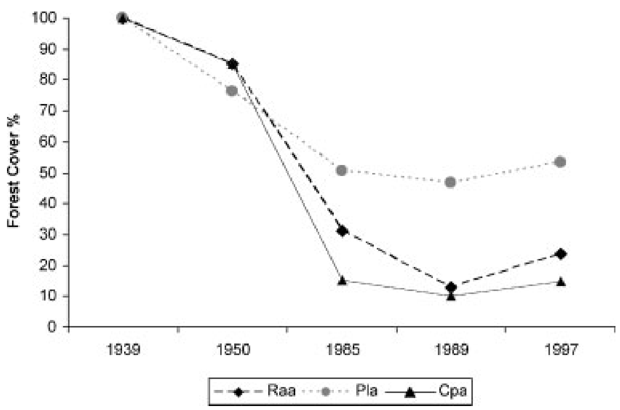

Figure 4. Forest loss by soil type

Table III. Annual deforestation rates for alluvial forests

Period	Total deforestation rate (per cent)	Anthropogenic deforestation (per cent)	Fluvial deforestation (per cent)	Average deforestation (ha yr^{-1})
1939–1950	1·66 per cent	0·96 per cent	0·70 per cent	30·4
1950–1985	1·60 per cent	1·25 per cent	0·35 per cent	24·0
1985–1989	3·42 per cent	2·29 per cent	1·14 per cent	22·5
1989–1997	1·78 per cent	1·47 per cent	0·31 per cent	10·1
Average	2·12 per cent	1·49 per cent	0·63 per cent	21·8

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coarse alluviums) soil type which is only flooded for 1 or 2 months annually (Figure 4) (IGAC Instituto geogrÃfico AgustÚn Codazi, 1978).

DISCUSSION

Few studies have addressed deforestation in Colombia (e.g. Etter and Andrade, 1987; Cavelier and Etter, 1996; Viþa and Cavelier, 1999; Mendoza and Etter, 2002), and none of these studies have investigated the deforestation process in alluvial forests. Examining the dynamics of alluvial deforestation is valuable since they influence key areas of the landscape of Colombia and have a complex occupational history.

Alluvial forests situated on recent fluvial sediments are often subjected to extreme conditions of drying and flooding during the year (Hiraoka, 1985). HCM forest types were historically found along the river's edge where annual flooding created highly fertile soils. Once common, this forest type is now rare along river edges, since much of it was originally cleared by logging and is now valuable for agriculture due to its easy accessibility and soils with relative higher fertility compared with highland soils (ORAM, 1998). Our findings support this with the persistence of forest fragments being strongly associated with soil types that are flooded more than 6 months per year, making them unsuitable for mechanised farming techniques.

Although the average deforestation rate of 2·12 per cent in our study area was greater than those found in a related study in the Casanare region (Viþa and Cavelier, 1999), peak deforestation rates did occur during similar time periods for both studies. Our maximum annual deforestation rate of 3·42 per cent occurred during 1985–1989, while the peak in Casanare of 4·4 per cent occurred in 1978–1988. This relationship between periods of peak deforestation rates are likely the result of a shift in land use from logging to agriculture during those years. During the 1989–1997 time period, deforestation rates dropped to 1·78 per cent for two principal reasons. First, LCM forest and young forest types were replaced by HCM forest types due to plant community succession. This reversal of deforestation towards forest growth was observed in the eastern part of the study area where a 500 ha reserve (Menegua Park) was created. A similar pattern has been documented in other tropical ecosystems (Lugo, 2002) due to a shift in land use patterns from agriculture to other uses. Second, remaining forest was unsuitable for mechanised farming techniques because they were flooded for at least 6 months of the year. Thus, deforestation rates peaked as logging became a dominant force in the area and later declined after timber harvest and other resource extraction were replaced by agriculture.

River dynamics can play an important role in the transformation of alluvial landscapes (Decamps and Naiman, 1989; De Jong, 1995; Kvist and Nebel, 2001; Parsons and Gilvear, 2002). Although river erosion was a constant force during all study periods, it became a significant cause of forest loss between 1989 and 1997. The negative effects of erosion have probably been exacerbated due to anthropogenic deforestation and agriculture. This eliminates riparian vegetation, and reduces bank stability (Nebel, 2001). Bank alterations can result in a wider and shallower active channel, which is more prone to annual channel migration.

Although in our paper we found that channel migration reduced HCM forest coverage and habitat complexity, Salo *et al*. (1986) found that river channel dynamics may cause HCM forest turnover rates through lateral erosion and channel migration, thus creating complex forest mosaics. These same authors calculated that 12 per cent of alluvial forests are in various successional stages in the Peruvian Amazon and suggested that river dynamics may be partially responsible for the high biodiversity common in the upper Amazon (Salo *et al*., 1986). This suggests that channel migration rate may regulate habitat complexity. At normal rates of migration, riparian plant communities will experience intermediate levels of disturbance. This creates a highly complex mosaic of patches in various stages of succession. When channel migration rates increase, as occurred in our study area, disturbance frequency may be greater than the succession rate of plant communities. Nebel (2001) believed alluvial floodplain ecosystems are adapted to localised, large landscape perturbations. We hypothesise that flood plain ecosystems may only be adapted to pulsed disturbances (where the variation occurs only once during the time of consideration) and unable to quickly recover from press disturbances (a continuous disturbance where the variation occurs at random time intervals and at random amplitudes) commonly associated with human activities (Jiang *et al*., 2000).

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Finally, spatially and temporally dynamic landscapes such as alluvial floodplains are difficult to analyse because fluctuating environmental parameters can result in a mosaic of micro-environments each with a unique history of plant succession. (Salo *et al*., 1986; Worbes *et al*., 1992; Worbes, 1997; De Jong *et al*., 2001; Nebel, 2001; Parsons and Gilvear, 2002). Although single, 'snap shot' observations of spatial relationships are certainly useful, landscape studies such as our own which examine temporal changes can reveal information critical to successful land management such as trends in land use and patterns of succession and thus, give an understanding of both pattern and process.

CONCLUSIONS

During the 58 yr study period, HCM and LCM forests have significantly decreased, producing a highly fragmented landscape. In our study, 72·6 per cent of the observed deforestation was related to human disturbance, while 27·4 per cent of forest losses were due to channel migration of the Meta River (Table III). High Canopy Mature forests were the most affected land cover since they are easily accessed, viable for logging and occurred on fertile soils which are valuable for agriculture. We have observed a dramatic reduction in the coverage of HCM forests (a loss of 70·4 per cent). This forest type contains most of the biodiversity of the region. So, much of the region's biodiversity may be lost. Finally, although we observed a reduction in deforestation rates, forest fragmentation has increased leaving remnant patches which are more prone to edge effects which may increase the loss of interior species in the local forests.

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