Carbon emissions from land-use change: a regional analysis of causal factors in Chiapas, Mexico.

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Abstract

This study examines the correlation between deforestation, carbon dioxide emissions and potential causal factors of land-use change within an area of 2.7 million ha in Chiapas, southern Mexico between 1975 and 1996. Digitised land-use maps and interpreted satellite images were used to quantify land-use changes. Geo-referenced databases of population and digitised maps of roads and topography were used to determine which factors could be used to explain observed changes in land-use. The study analysed the relationship between carbon emissions during this period and two types of possible causal factors: ´predisposing' factors that determine the susceptibility of a particular area of forest to change (slope gradient, distance to agriculture and roads, land tenure) and 'driving' factors representing the pressures for change (population density, poverty). The correlated factors were combined in risk matrices, which show the proportion of vulnerable carbon stocks lost in areas with defined socio-economic characteristics. Such matrices could be used to predict future deforestation rates and provide a verifiable evidence-base for defining baseline carbon emissions for forest conservation projects. Based on the results of the analysis, two matrices were constructed, using population density as the single most important driving factor and distance from roads and distance from agriculture as the two alternatives for the predisposing factors of deforestation.

Key words: baselines, carbon emissions, deforestation, forest conservation, land-use change, risk matrices

1. Introduction

Anthropogenic land-use CO_2 emissions originate essentially from tropical deforestation. Global deforestation rates between 1970 and 1990 were 15.1 million ha yr-1 (Dixon *et al.* 1994) and estimated annual average emissions from deforestation in the 1990's were 1.6±0.8 GtC yr^{-1} (Houghton 1999). The annual rate of deforestation in Mexico between 1990 and 1995 was around 1% (FAO 1999) and according to Masera *et al.* (1997) land-use change in Mexico accounts for approximately 35% of the country's total annual carbon emissions.

Although the anthropogenic CO_2 emissions from land-use change in developing countries represent between 20 to 30 percent of all anthropogenic CO_2 emissions, projects that reduce deforestation have been excluded from the first commitment period of the Clean Development Mechanism (CDM). One of the uncertainties related to the acceptance of forest conservation projects as a legitimate means of compliance with international emission reduction targets is that tropical deforestation is still poorly understood. Skole (1994) identifies a number of knowledge gaps: a lack of accurate measurements of its rate, geographical extent, and spatial pattern and a lack of insight into its causes. Various studies point out that tropical deforestation is the consequence of a variety of interrelated social, economic, and environmental factors (Geoghegan *et al.*, 1998; Skole *et al.*, 1994; Walker, 1987), although Malthusian explanations for deforestation also remain central to many analyses (e.g. Harrison, 1991).

The way in which these factors interact with deforestation appear to vary significantly between regions. According to FAO (1996) changes in tropical forest cover in the

1980’s in Africa were driven mainly by rural population expansion, in Latin America deforestation was driven by centrally planned operations such as resettlement, cattle ranching and hydroelectric schemes; while in Asia deforestation resulted from a combination of both factors. At a national/regional level, changes in land-use may be correlated with more specific factors relating to climate, topography, access, demography and various socio-economic conditions. For example, Harrison (1991) found that population growth in Costa Rica between 1950 and 1984 was strongly correlated with deforestation in some regions but not in others; the effect of population growth on deforestation depended on other factors including the rate of urbanisation and the number of immigrants in the population. Sader and Joyce (1988) found that deforestation in Costa Rica was also strongly related to other factors including distance to roads, slope gradient, eco-region and protection status.

The interactions between different social groups, land tenure and access also play important roles. Deforestation may occur through a sequence of processes, for example logging operations followed by ranching and/or clearance by small-scale farmers in which each process is determined by a specific set of causal factors (Walker, 1987). Where land is already populated and few large areas of wilderness still exist, deforestation is more likely to occur in a piecemeal fashion as current areas of agricultural land are extended. Where population is low and settlements are sparse the rate of deforestation may depend more on the accessibility of the forest areas through road construction. Steep terrain may be an impediment to agricultural expansion where land is plentiful but where land is scarce other pressures may eventually drive farmers to clear forests on ever-steeper slopes (Ochoa and González, 2000). Other socio-economic factors, which may vary from region to region, will also have an effect; for example where the prevailing land-use is large-scale cattle ranching large areas of forest may be cleared with few people, in contrast the population in regions with intensive agricultural systems may increase while maintaining natural forest cover. Skole *et al.* (1994) stated that regional trends may be influenced by external policy factors, such as taxes and market prices, but that these are mediated by local-scale conditions. Veldkamp and Lambin (2001) further point out that variation in explanatory variables of land-use change with scale follow a certain pattern: at farm level, social and accessibility factors play a role, at the landscape level, topography and agroclimatic potential seem to be the main determinants, while at a regional level, climatic variables as well as macro-economic and demographic factors appear to drive land-use.

2. Methods

This study examines the relationships between CO_2 emissions from deforestation and various potential causal factors of change within an area of 2.7 million ha in Chiapas, southern Mexico, between 1975 and 1996 (Figure 1). Carbon emissions were calculated using information derived from land-use maps and satellite images and published and unpublished data on vulnerable carbon stocks (i.e. that carbon expected to disappear quickly when land-use changes from a forested to non-forested land cover). The relationships between the carbon emissions and two types of possible causal factors were examined:

(a) ‘Predisposing’ factors that determine the susceptibility of a particular area of forest to change (slope gradient, distance to agriculture and roads and land tenure) and

(b) ‘Driving’ factors representing the pressures for change (population density and poverty).

Those factors that were strongly correlated with CO_2 emissions were then combined in risk matrices each containing up to 12 classes. The rate of deforestation observed in each class over the 21-year study period was then calculated.

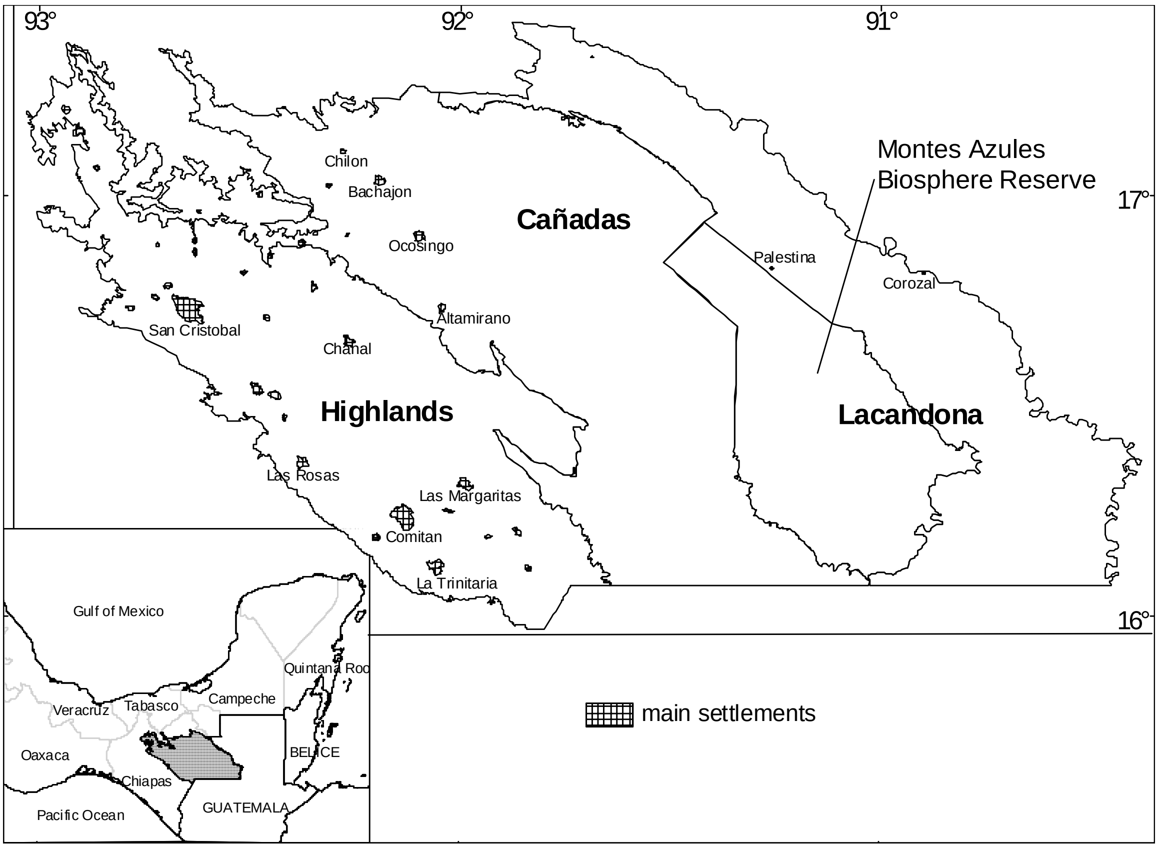
2.1 The Study area

Chiapas contains one of the richest biotas of Mexico with some 9000 species of vascular plants known and described (Breedlove 1981). The area encompasses a wide variety of environmental conditions, ranging from tropical humid lowland to montane sub humid climates. Following this elevation and humidity gradient a wide variety of forest types are present, including evergreen cloud forest, pine and oak forest complexes, and evergreen and semi-evergreen lowland rainforest (De Jong *et al.* 1999).

In contrast to its biological richness, Chiapas is considered as one of the poorest states in Mexico (World Bank 1995). The study area includes a range of socio-economic conditions similar to those found throughout Central and South America. Subsistence agriculture is the most important economic activity, traditionally involving the Mayan 'milpa' system of shifting cultivation, in which forest is cleared to grow maize and beans in a labour-intensive, rain-fed system. In recent decades, the traditional milpa system has been intensified in most areas due to increased pressure on land, shifts from subsistence to commercial production and widespread application of fertilizers (Ochoa and Gonzalez 2000). Approximately 70% of the study area is held under a form of communal land tenure known as the ejido system, established after the 1910 Mexico revolution when large areas of private land were redistributed to the landless poor.

Although socio-economic and political conditions vary widely across the area, three sub-regions could be distinguished, based on demographic, political and environmental characteristics: the Highlands, the Cañadas, and the Selva lowlands. However, there is no established precedent for defining the exact geographical limits of each region; administrative boundaries on their own do not adequately describe these regions, due to the range in size of the municipalities (administrative unit, comparable with county). Since many of the socio-economic patterns observed in the study area appeared to be closely associated with certain environmental conditions, the areas with similar climates could be grouped together and subsequently separated by particular administrative boundaries, such as the Monte Azules reserve (Figure 1).

Figure 1: Study area with three sub-regions and one major protected area.



2.1.1 The Highlands: 0.7 million ha; montane-tropical humid to sub humid. The most important forest types that occur here are pine, pine-oak and oak forest, with evergreen cloud forest at the higher altitudes (Miranda and Herández 1963, Breedlove 1981, González *et al.* 1995). Up to a few decades ago, large areas were covered by old-growth forest but the highlands are now characterized by a highly fragmented landscape of cultivated land, tree and shrub fallow, permanent and temporary pasture and perturbed and open forests (González *et al.* 1995). Maize is the most important crop in the region; other economic activities include local employment and low intensity cattle rearing. The highlands are the most densely populated rural area of Chiapas with a population density of approximately 80 persons per km^2 (Tipper *et al.* 1998), of which 70% are from indigenous ethnic groups (Fernández *et al*. 1999). Major towns in the area include San Cristóbal de Las Casas (1990: 73,400 inhabitants), Comitán (48,300), and Las Margaritas (8,640).

2.1.2 The Cañadas: 1.1 million ha; sub-tropical humid to sub humid. The region covers the transition zone between the mixed tropical forests of the lowlands and the pine and oak forests of the Highlands. Forest remnants in this area are restricted to inaccessible places and most of these have been extensively harvested in the past for commercial species. Maize production here involves the use of short rotation fallows; fertilizers are combined with short fallow periods, mainly to preserve soil from erosion on steeper slopes. The most important economic activity is the production of coffee. Other economic activities include temporal urban employment, either locally or in larger towns outside the region and cattle rearing. The region has a high population density and has been colonized by many ethnic groups from other parts of Chiapas. Major towns in the region are Ocosingo (1990: 12,800 inhabitants) and Yajalon (10,000 inhabitants).

2.1.3 The Selva lowlands: 1 million ha; tropical humid and sub humid. The original vegetation is broadleaved, evergreen tropical rainforest. The Selva Lowlands is part of the largest area of tropical humid forest in Central America (Medellin 1994), and includes the Monte Azules Biosphere reserve (0.3 million ha). Substantial colonization from other parts of Chiapas and Mexico has taken place over the past 50 years with large areas of forest converted to pasture land and agriculture. State and federal government policies in the 1970's and 1980's encouraged the settlement of farmers in the Marques de Comillas region that borders Guatemala to alleviate population pressure in other parts of the country. Principal economic activities are maize production and cattle ranching. The Selva lowlands does not contain any town with more than 5,000 inhabitants (as of 1990).

2.2 Analysis of Land-use Change

Estimates of deforestation were derived from a comparison of land-use data from the 1970's and 1990's. A number of 1:250,000 scale land-use/vegetation maps, produced by the national institute of geographic statistics and information (INEGI 1984, 1987, 1988; SPP-INEGI 1984), were digitised into Arc/Info format. The individual maps were joined into a single layer in a Transverse Mercator projection following edge-matching procedures. The original maps were based on aerial photographs dating from 1973-78 (scale 1:50,000 and 1:70:000), in which 71 land-use/land cover classes were distinguished. We assigned a nominal date of 1975 to this layer corresponding to the mean of the air photo dates (De Jong *et al.* 1999).

The 1990´s data were derived from classified Landsat TM satellite images from 1995-97 (corresponding to path 022 row 048 in 1995, path 021 rows 048 and 049 in 1996 and path 020 row 048 in 1997). Each satellite image was independently classified applying an automatic classification process. Training sites were established using data from ground-truthing, black and white 1996 aerial photographs taken at a scale of 1:75,000, and digital colour video footage (scale 1:20,000). Each satellite image was classified into up to 34 land-use classes and the separate images were then combined to cover the whole study area. A manual re-classification procedure was applied with aerial photographs as a reference to rectify areas with haze and shade in the satellite images. Subsequently, a low pass filter was employed to the classified satellite images to improve the spatial compatibility with the 1970's land-use data. The filter moderated the border effect and eliminated patches of less than 5ha.

In order to compare land-use data between the two time series, the land-use classes of each source were regrouped into six composite classes, which could be considered homologous in terms of land-cover characteristics and carbon density (See also De Jong *et al*. 1999; 2000):

1. Non- or little-disturbed tropical evergreen and semi-evergreen rainforest; including mature and secondary forest.
2. Disturbed tropical forest resulting from shifting cultivation practices, which at a landscape level produces a mosaic of mature forest mixed with patches of successional stages of secondary shrub and tree vegetation.

3. Non-disturbed montane/subtropical forest; including evergreen cloud forest and pine-oak and oak forest complexes.
4. Disturbed montane/subtropical forest resulting from grazing, small-scale agriculture, firewood collection, etc, producing a landscape dominated by open forests with little understory vegetation
5. Agriculture (tropical and temperate); including areas of early successional fallow vegetation dominated by herbaceous plants, as well as land currently under agricultural production
6. Pasture (tropical and temperate); including cultivated and induced pasture, abandoned grazing land and palm-dominated vegetation

2.3 Analysis of carbon emission

Estimates of carbon emissions resulting from land-use change were based on differences between the estimated densities of the ‘vulnerable’ carbon of the six composite classes (Table 1). De Jong *et al*. (1999, 2000) estimated carbon densities for various vegetation types in tropical and subtropical/montane regions of the study area. Data on the main carbon pools were collected in 68 plots of 0.54 ha each. The number of plots in each composite class was determined according to the relative importance of the land cover class and expected variability of the carbon pools: 39 plots were measured in the montane/subtropical highlands region and 29 in the tropical lowlands. (For a detailed description of the methodologies employed refer to De Jong *et al*. 1999, 2000).

Table 1. Aboveground and vulnerable C-density in the composite classes

Vegetation type	Aboveground C density ($tC\ ha^{-1}$)	Vulnerable carbon ($tC\ ha^{-1}$)
Tropical region		
Non disturbed Forests	233.4	221.3
Disturbed Forest	116.1	104.0
Agriculture	12.1	0
Temperate region		
Non disturbed forest	135.4	123.3
Disturbed forest	69.1	57.0
Agriculture	12.1	0

The vulnerable carbon is defined here as the fraction of biomass that is susceptible to disappear quickly as a result of human interference. It was assumed that carbon in the aboveground biomass will be lost very shortly after deforestation, whereas soil carbon in agricultural land and pasture will remain relatively unchanged. The vulnerable carbon in the composite classes can thus be calculated as the difference of the total amount of carbon present in the particular land-use type and the carbon found in agriculture/pasture in the same eco-region. Only carbon emissions resulting from deforestation were considered in this analysis, carbon emissions resulting from change of non-or little disturbed forest to disturbed forest were not taken into account.

2.4 Causal factors of change

A total of six socio-economic variables were constructed and tested for their relationship with deforestation and related carbon emissions by calculating the correlation coefficients for each of these variables with deforestation between 1975-1996. Each socio-economic variable was categorized into a series of discrete classes and spatially distributed in the form of a GIS-layer. The map generated for each variable was then superimposed over the deforestation map to calculate the rate of deforestation in each class of the variable, spatially represented as homogeneous polygons. The Spearman's rank correlation coefficient was calculated for the whole study area and separately for each sub-region. Factors that showed a significant correlation coefficient were then reclassified into 3 to 4 classes. Various combinations of classes were tested for each factor to produce the most significant, unidirectional trend in deforestation.

2.4.1 Predisposing factors

Slope gradient

Forests on steeper slopes are generally more difficult to clear and the soils are more vulnerable to erosion; we therefore expected that slope gradient will be negatively correlated with deforestation. To test this hypothesis, a digital map of slope gradients was derived from a digital elevation model constructed from digitised 1:250,000 topographic maps (INEGI, 1996). Gradients were grouped into three classes, similar to those of Touber *et al.* (1989): lowland plains and low slopes (0-9º), hills and low escarpments (9-17º) and steep hills and high escarpments (>17º).

Distance from roads

Forests that are closer to roads will normally be more accessible and hence more easily cleared for agriculture and pasture. This hypothesis was tested by creating "buffer" areas around roads and calculating deforestation in each of the buffer zones. Distances were initially classified in ranges of 100m and then grouped into three classes that showed the highest correlation with deforestation: 0-1000m, 1000-2000m and >2000m. Although data on distance from roads were not available from the start of the study period, a 1:50,000 road map of 1980 was available. As little road building took place between 1975 and 1980 this map was used to analyse how roads present at the start of the study period affected land-use change over the following 21 years.

Distance from agriculture

It has also been pointed out by other studies that the accessibility of forest areas is influenced by their proximity to existing areas of agriculture and pasture, especially in areas already affected by deforestation (Rudel and Roper 1997). Buffer zones around agriculture, pasture and other disturbed land present in 1975 were created in a GIS and the correlation coefficients between deforestation rates and the distance from the forest edge calculated. Distances were initially classified in ranges of 100m and were then grouped into three classes that were highly correlated with deforestation: 0-500m, 500-1000m and >1000m.

Land tenure

The tenure of land is an important factor in the land-use decision-making process. The main types of land tenure in Mexico are: national reserves, private property and communal land (ejidos and indigenous lands). The data for this analysis were derived from the 1991 agricultural census (INEGI, 1991), which uses Basic Geo-Statistical Units (AGEB, for its abbreviation in Spanish) as the unit of analysis. Each AGEB was classified according to its dominant land-tenure type. Where there was no clear predominant land tenure, the AGEB was classed as ‘not defined’.

2.4.2 Driving factors

Rural Population density

Population density, particularly in areas of high poverty and scarcity of agricultural land, is widely considered as one of the most important driving factors of deforestation. To test this hypothesis in our study area, a population density map was created from the 1990 national population census (INEGI, 1991), which provides data at the level of geo-referenced settlements. (Data prior to 1990 are only available at the level of the municipality, and are not suitable for this analysis due to the large size of some municipalities.) The area of influence of each locality was defined as a circle with a radius of 3 km around its centre, based on the average distance travelled to agricultural fields as reported by farmers in the study region. The number of inhabitants active in the agricultural sector was used to calculate the population density within this area of influence. When the area of influence one settlement overlapped with another, the sum of the densities of each settlement was applied in the area of overlap. Population densities were initially classified in ranges of 5 farmers/km^2 and subsequently grouped into four classes with the clearest trend in deforestation: 0, >0-15, >15-30 and >30 farmers per km^2.

Poverty Index

Criteria to indicate the level of poverty generally rely on the level of income or expenditure of a population (Henninger 1998). However, in Chiapas most small-scale farmers rely completely or partly on subsistence agriculture and hence may not be involved in the external economy. We therefore constructed an index, based on the access to education and housing conditions, using the following indicators from the 1990 census (De la Torre 1996):

Proportion of the population with the following educational characteristics:

1. Aged between 6 and 14 that did not attend primary school
2. Aged between 6 and 14 that cannot read or write
3. Older than 15 that have not completed primary school
4. Older than 15 that did not attend secondary education
5. Older than 15 that cannot read or write

Proportion of houses with the following conditions:

1. Houses with only one room
2. Houses with cardboard walls
3. Houses with cardboard roofs
4. Houses with earth floors
5. Houses without electricity
6. Houses without piped water
7. Housed without drainage

The index is a number between 0 (no lack of access) and 1 (complete lack of access), was then grouped into three classes such that each class represent more or less the same surface area in the study region: Low (0-0.6), Moderate (0.6-0.8) and High (0.8-1). For each settlement the value of the index was calculated. This index was then extrapolated to each spatially explicit AGEB unit.

2.5 Construction of risk matrices

Risk matrices were then constructed by combining factors that had shown the highest unidirectional correlation with deforestation and CO_2 emissions. One predisposing and one driving factor, each with 3 or 4 classes, were combined to produce a risk matrix with up to 12 cells. A GIS layer with the spatial distribution of the value of each cell of the risk matrix across the study area (each cell forming homogeneous polygons) was then superimposed over the 1975-1996 deforestation map. From the resulting overlay, deforestation, expressed as the average percentage of forest lost in each class during the study period, was calculated.

3. Results

3.1 Deforestation

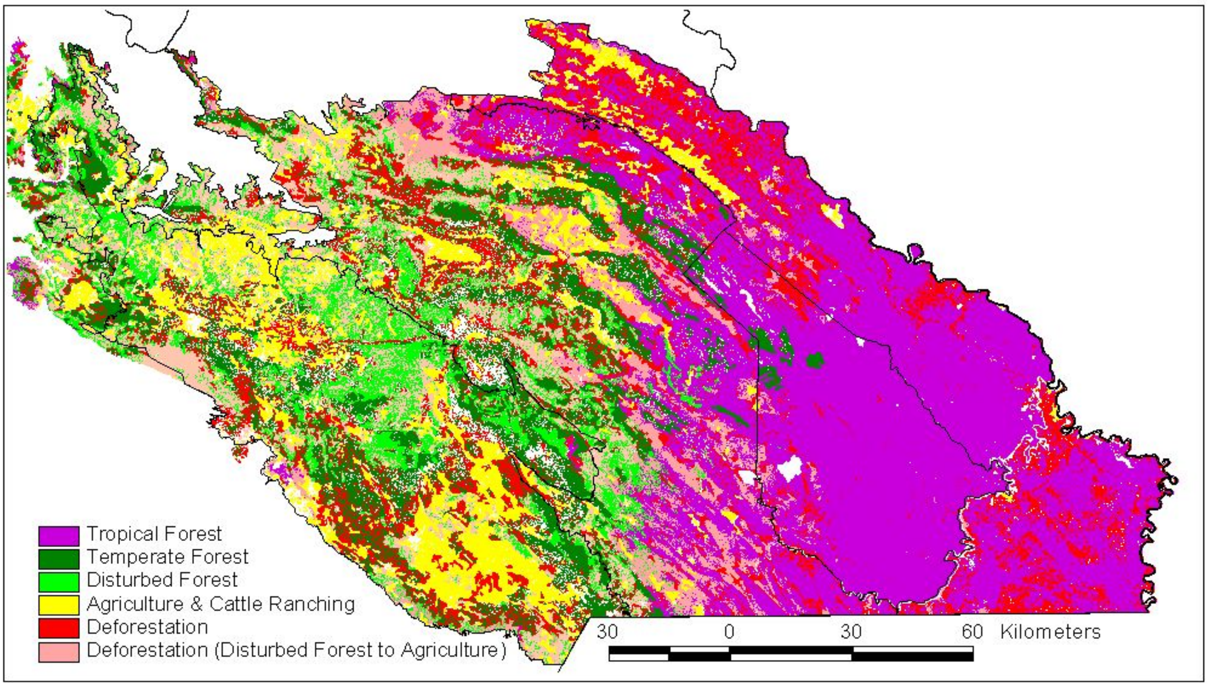
Table 2 shows the area covered in 1975 and 1996 by each of the six composite land-use classes. In total 412,000 ha of montane forest and 379,000 ha of tropical forest were lost during this period, representing annual rates of deforestation of 2.3% and 1.6% respectively. However, as can be seen from Figure 2, forest cover in the Montes Azules Biosphere reserve in the Selva region remained largely intact. If the area of the reserve is excluded from the analysis the deforestation rate for tropical forest was 2.1%/yr.

Table 2. Land cover in 1975 and 1996, and annual deforestation rate.

Vegetation type	1975 (ha)	1996 (ha)	Annual deforestation rate	
Tropical Forest	1,052,059	912,353	1.6%	
Disturbed Tropical Forest	239,301	n.d.[1]		
Montane Forest	600,015	514,931	0.7%	2.3%
Disturbed Montane Forest	469,821	142,124	5.5%	
Agriculture	192,824	894,094		
Pasture	156,297	223,196		

[1] n.d. = not distinguished from undisturbed tropical forest

Figure 2: land use change in study region 1975-1996

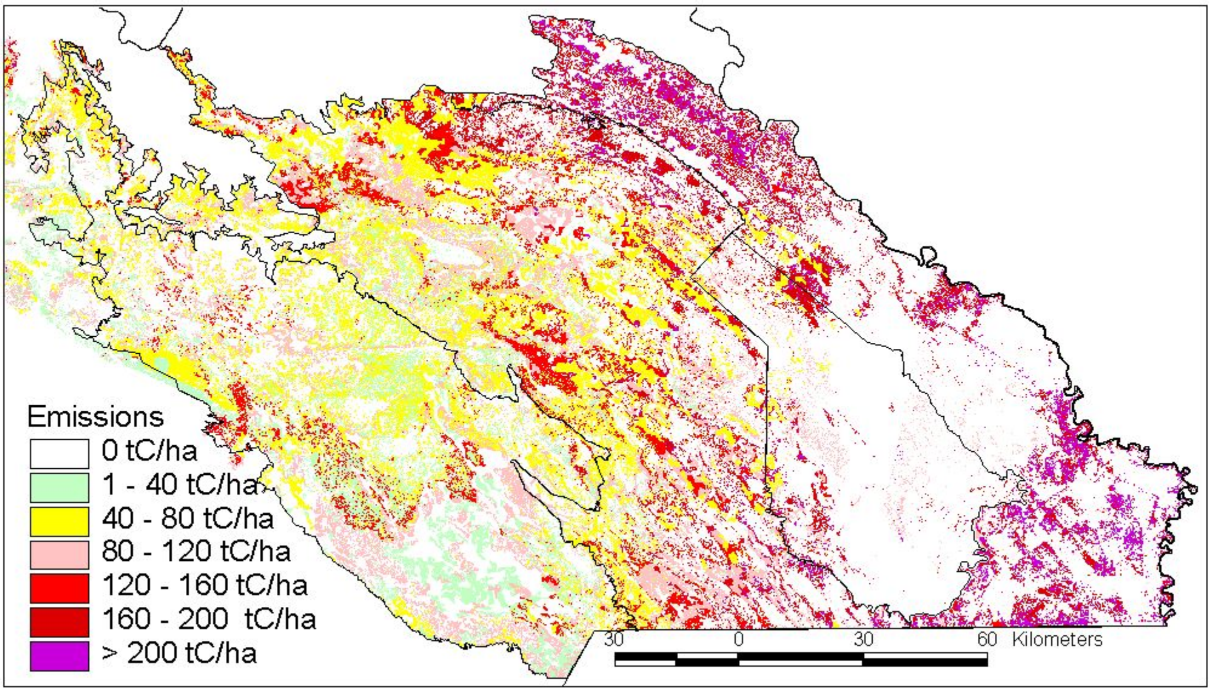


In the Highlands sub-region, most of the deforestation occurred in already disturbed forest. It was not possible to distinguish non-disturbed and disturbed tropical forest in the satellite images, so we could only calculate the total deforestation for tropical forest, but it is clear from Figure 2 that large areas of non-disturbed tropical forest were lost in the Selva sub-region. In the Highlands and Cañadas the pattern of deforestation was patchier.

3.2 Carbon emissions

The total CO_2 emissions resulting from deforestation over the period of 1975-1996 were 86 million tonnes of C (tC). Emissions from the Cañadas sub-region were highest, around 35 million tC, emissions from the Selva were 31 million tC and those from the Highlands 20 million tC. This is partly due to the relative size of the three regions but also reflects the trends in deforestation. Figure 3 shows the distribution of emissions across the study area. Note that while emissions in many parts of the Selva region were estimated at zero, where deforestation did occur the resulting carbon emission per ha was very high, reflecting the large loss of vulnerable carbon when non-disturbed tropical forest is cleared. By contrast deforestation in the Highlands was more widespread but tended to result in lower emissions per ha due to the lower vulnerable carbon stock of disturbed montane forests cleared in this area.

Figure 3: carbon emissions (tC/ha) in the study region from 1975 to 1996



3.3 Correlation between deforestation and factors of change

3.3.1 Land tenure

Data in table 3 indicate a potentially significant relationship between tenure and deforestation over the study area as a whole and in each of the separate regions.

Deforestation was higher in private property than in communal land, the difference being greatest in the Selva region. However, the difference between reserve and non-reserve land was much greater; deforestation in reserves was consistently lower than any other land tenure class. For this reason the Montes Azules Biosphere was excluded from further analysis.

Table 3. Deforestation between 1975-1996 in each region for three types of land tenure.

region	Reserves	Communal land	Private property
Highlands	n/a[1]	40.3%	46.0%
Cañadas	17.2%	47.2%	53.2%
Selva	14.8%	36.3%	62.5%
Total study area	***11.4%***	***42.3%***	***49.8%***

[1] n/a = not applicable

3.3.2 Other factors

Table 4 shows that distance from roads, distance from agriculture, and population density were all highly correlated with deforestation, with correlation coefficients all greater than 0.9 and all significant at the 0.01 level. Deforestation decreased with increasing distance from roads and distance from agriculture, and increased with increasing population density. Slope gradient was not correlated with deforestation in the Selva sub-region or in the study area as a whole. However, gradient was significantly correlated with deforestation in the Highlands and the Cañadas, where deforestation decreased with increasing gradient.

Table 4 Spearman's correlation coefficients between deforestation and causal factors of change by region

Causal factor	Study area	Highlands	Cañadas	Selva
Slope gradient	0.117	0.900**	0.817**	-0.650
Distance to roads	1.000**	1.000**	1.000**	1.000**
Distance to agriculture	0.997**	0.988**	0.996**	0.999**

Population density	0.984**	1.000**	1.000**	0.927**
Scarcity index	0.886 *	0.829 *	-0.900 *	0.771

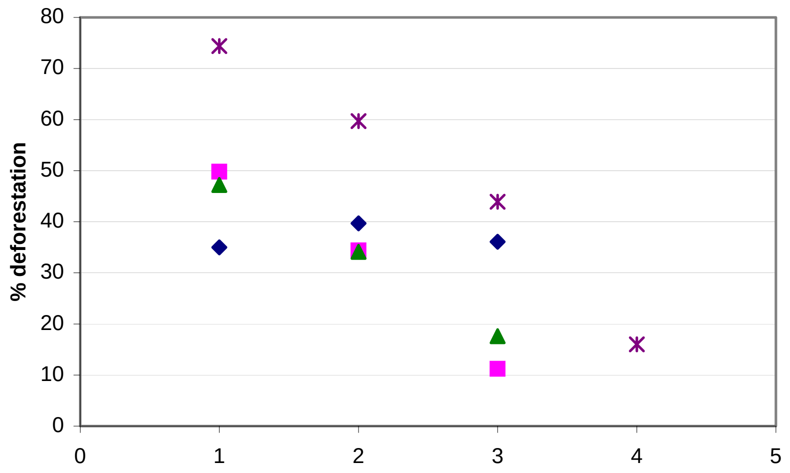
** Significant at 0.01 level
* Significant at 0.05 level

The poverty index was weakly correlated with deforestation; varying from non-significant in the Selva region and only significant at the 0.05 level for the other sub-regions. It is interesting to note the opposite trends in the Highlands compared to Cañadas: deforestation was higher in areas of high poverty in the Cañadas, but in the Highlands deforestation was higher in areas of low poverty.

Figure 4 shows that distances from roads, distances from agriculture and population density all show clear and generally linear trends with deforestation for all regions. Poverty is not shown due to the low level of significance obtained for this factor. In the Cañadas, deforestation appears to decrease linearly with increasing gradient, although the differences are small. However, in the Highlands the relationship between gradient and deforestation is non-linear despite the significant result in the correlation analysis, possibly due to the grouping of the gradients in the three classes.

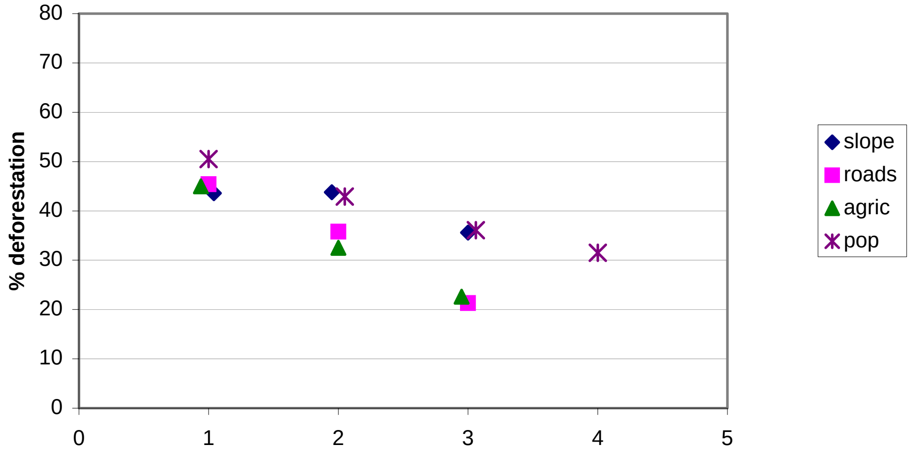
Figure 4 Deforestation in % of 1975-forest for each class of the factors: gradient (slope), distance to road (roads), distance to agriculture (agric), and population density (pop) for: A: Whole study area; B: Highlands; C: Cañadas; D: Selva

A



Class	1	2	3	4
◆ slope	0-9º	9 – 17º	>17º	
■ roads	<1000	1000-2000	>2000	
▲ agric	<500	500-1000	>1000	
✳ pop	>30	15-30	0-15	0

B



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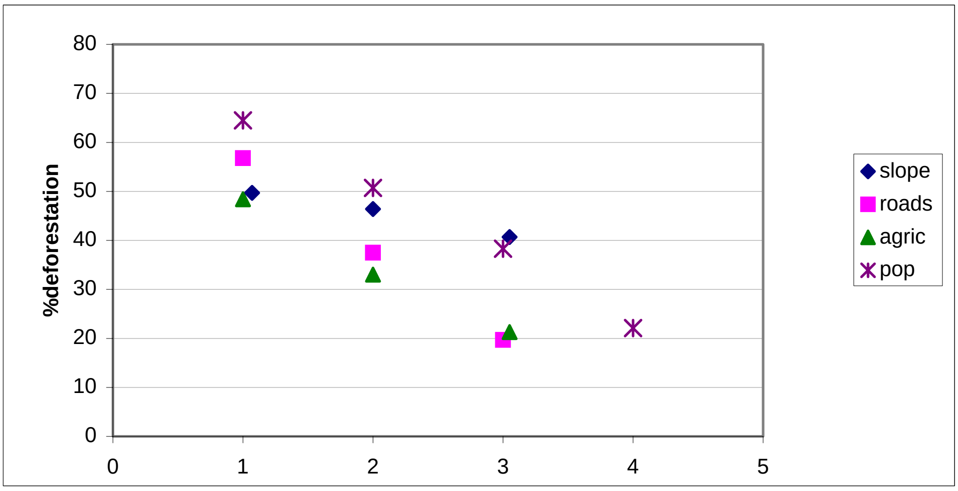

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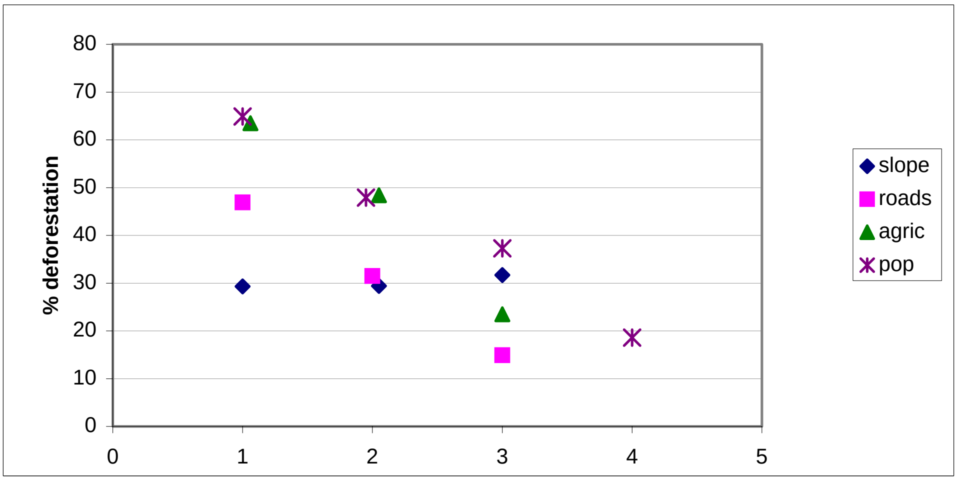

In general, the effect of distance from roads, distance from agriculture and population density on deforestation was more pronounced in the Selva and Cañadas than in the Highlands. Taking population density as an example, deforestation decreased from 65 to19% from high to low population density in the Selva, from 65 to 22% in the Cañadas but only from 51 to 32% in the Highlands.

3.4 Risk matrices

Based on the results of the above analysis two risk matrices were constructed, using population density as the driving factor and distance from roads and distance from agriculture as the predisposing factors of deforestation (see Tables 5 and 6). Each matrix has 12 categories and each cell value represents the average percentage of deforestation between 1975 and 1996 for this particular category.

Table 5. Risk matrix for population density and distance to road (% deforestation 1975-1996).

Population density (hab/km2)	Distance from roads (in m) 0 - 1000	1000 - 2000	>2000
> 30	77.8%	61.8%	41.7%
>15 - 30	66.7%	50.1%	33.7%
> 0 - 15	54.9%	38.2%	24.2%
0	42.8%	25.4%	6.7%

Table 6. Risk matrix for population density and distance from agriculture (% deforestation 1975-1996).

Population density (hab/km2)	Distance from agriculture (m) 0 - 500	1500 - 1000	>1000
>30	62.7%	52.2%	47.8%
>15 - 30	54.7%	42.1%	36.4%
>0 - 15	47.7%	33.8%	26.3%
0	39.7%	27.3%	10.8%

The matrices show two clear linear trends: 1. Increasing deforestation from low to high population density and 2. Decreasing deforestation when increasing the distance from roads or agriculture. Deforestation increases across the matrix from 7% in areas with zero population density at a distance of more than 2km from a road to 78% in areas with more than 30 farmers/km^2 and closer than 1000m to a road (Table 5). Deforestation also increases across the matrix from 11% in areas with zero population density and at a distance of more than 1km from agriculture to 63% in areas with more than 30 hab/km^2 and closer than 500m to agriculture (Table 6).

4. Discussion

4.1Deforestation and carbon emissions

Approximately 86 million tonnes of carbon were emitted to the atmosphere due to deforestation in the study area between 1975 and 1996. The actual total is likely to be higher than this as emissions from forest degradation were not included in our calculations. This is equivalent to 59% of total carbon emissions from the UK in 1999. This is clearly a significant quantity of greenhouse gas emissions from an area approximately 1/3 of the size of Scotland.

Carbon emissions were generally higher in the Cañadas and Selva regions than in the Highlands. Although the Highlands has the highest population density of the three regions, historic land-use change had already resulted in a highly fragmented forest by 1975, and the piecemeal clearance of open forest over the following 21 years resulted in widespread but generally low intensity emissions. The Cañadas also has a relatively high population density but has undergone more significant changes in production systems in the last two decades with larger areas of undisturbed forest cleared for coffee production and cattle rearing. In the Selva, rapid population increase due to government policy induced colonization by new groups resulted in large areas of previously non-disturbed forest being cleared, mainly for extensive cattle grazing.

4.2 Causal factors

4.2.1 Population density

Population density consistently displayed the clearest correlation with deforestation across all regions, with higher deforestation occurring in areas with higher population densities. This relationship was strongest in the Cañadas and in the Selva with a less pronounced but still clear trend in the Highlands. It should be noted that the Selva region has been recently colonized and most of the area had low levels of population density at the start of the study period. While this does not invalidate the result it does raise the question of whether this trend would be continued in the future. However, given the strength of the observed relationship we conclude that population density is a good indicator of deforestation in all regions.

While population density is often a good indicator of deforestation it is difficult to represent in a spatial manner since it requires an analysis of the area over which a population has an effect as well as the numbers of people living in particular localities. In this study population density was expressed by defining the area of influence for each locality as a circle of 3 km radius. We suggest that further work could be undertaken to examine the appropriate shape and size of zones of influence from different types of settlement based on population size and land tenure.

4.2.2 Distance from roads/agriculture

Both distance from roads and distance from agriculture appear to be good indicators of deforestation between 1975 and 1996. Strong, linear relationships were observed between deforestation and both factors in all regions, with deforestation increasing with increasing proximity to both roads and agriculture. We conclude that the accessibility of the forest is an important causal factor for deforestation in the study area. The correlation between deforestation and forest accessibility was more pronounced in the Cañadas and Selva than in the Highlands. In the Selva region distance from agriculture appeared to have a greater effect on deforestation than distance from roads. However, this may be due to the fact that the Selva is a zone of recent colonisation and there were few areas of agriculture at the start of the study period; although deforestation was higher in areas close to agriculture, in absolute terms 70% of all deforestation in the Selva region occurred in areas further than 1km from agriculture present in 1975.

4.2.3 Slope gradient

Relationships between gradient and deforestation were not as clear as for other factors; high levels of poverty and population pressure in the study area mean that gradient is not always a barrier to deforestation as farmers resort to steeper areas to clear for agriculture. This factor was therefore not considered to be a good indicator of deforestation in the study area and was not included in the risk matrices. This finding is consistent with Ochoa and Gonzalez (2000), who reported similar results for the Highlands sub-region.

It is also interesting to note that, although gradient had been significantly correlated with deforestation in Highlands and Cañadas, when gradient was reclassified into three classes no unidirectional trend was observable in the Highlands. While it is necessary use a small number of classes to keep risk matrices relatively simple it should be noted that the process of re-classifying variables can change the relationship and the criteria for defining risk classes must be clearly set out.

4.2.4 Poverty index

Deforestation was not clearly correlated with our poverty index. It is interesting to note, however, that poverty appears to have opposite effects on deforestation in the Highlands and the Cañadas. Poverty is often quoted as a driving factor of deforestation, as poor farmers rely more heavily on natural resources to supply their needs. This may be the case in the Cañadas where deforestation was higher in areas of high poverty, but the opposite trend was observed in the Highlands. One possible explanation for this is that many farmers in the Highlands use spare income to invest in cattle, as a form of capital savings. Richer farmers, who can buy more cattle, will require more land for pasture and this may explain the negative relationship between poverty and deforestation in the Highlands.

4.2.5 Land tenure

It is clear that deforestation has been almost nil in reserves, where controls over resource use are strong and where sufficient financial resources are available to ensure that the protective status is maintained. Deforestation was always higher in private property than in communal land. The relationship was strongest in the Selva sub-region, although it should be noted that private property makes up less than 2% of this region. This would suggest that management of forests resources in communal lands has been more conservative over the past 20 years, contradicting theories that common resources are more likely to be degraded through a lack of control mechanisms (e.g. Hardin 1968). However, it is also possible that deforestation in communal land has been lower because communities lack financial resources to invest in other land uses, for example cattle ranching, which may be available to private owners.

4.3 Predicting future emissions

In developing countries, the building of roads, the development of centres of employment and the promotion of agriculture production are important elements of economic development. However, these actions also have an effect on land-use change and related carbon emissions. Policy makers, who must find a balance between promoting economic development and controlling climate change, need information on how such activities affect carbon emissions. This study clearly shows that the assessment of future deforestation and related emission scenarios requires spatially explicit analysis and cannot rely on simple extrapolation of current deforestation rates into the future.

One of the challenges of analysing regional trends in deforestation is the definition of the regions used in the analysis. This can have a major effect on the results, for example, in our analysis slope gradient was not significantly related to deforestation in the whole study area, but was correlated with deforestation in the Highlands and Cañadas sub-regions. It is therefore of primary importance that regions are defined according to a logical grouping of demographic, economic and environmental characteristics. It is also necessary to define the geographic scale of the analysis. We have used socio-economic characteristics to define homologous polygons within the study area within which the average rate of deforestation and carbon emissions were calculated. To be effective, information to support land-use decision and policy must be based on a simple, replicable analysis, providing maximum information with a minimum level of complexity. While a pixel level analysis (e.g. Geoghegan *et al.* 1998) might provide detailed information of why changes take place at the exact plot, such an approach would be too complex to apply in many circumstances. The aim in this paper has therefore been to balance the need for detailed information on the spatially distributed risk of carbon emissions with a model that is relatively easy to use.

We propose that the approach of establishing risk matrices to estimate deforestation and carbon emissions developed in this study could be used to provide a verifiable evidence-base for defining ‘business as usual’ baselines to quantify emission reductions from forest conservation and management projects. The methodology uses readily available socio-economic information and, while the parameters associated with deforestation may differ from country to country, could be applied relatively easily in most regions. In a separate paper we present an application of the methodologies developed here to predict land-use change and carbon emissions at various spatial scales in the study area (Hellier *et al.* 2002).

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