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RESEARCH PAPER

# Spatial Modeling of Tropical Deforestation Using Socioeconomic and Biophysical Data

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**Abstract** Tropical forests are disappearing at an alarming rate. In Central America, a hectare of forest is cleared for agriculture every 5 min. This study was conducted in a forested 4,000 ha watershed of central Honduras to find deforestation causes based on socio-economic characteristics of population. First, a multitemporal analysis of Landsat TM imagery was conducted to determine deforestation rates and agricultural–forest boundaries. A GIS buffer procedure allowed determining which households were at the *deforestation front* and which households were located at the rest of the area (control). GIS techniques were used to extract biophysical information such as slope, elevation, land cover, temperature, precipitation, etc. Then, we set up a data base with more than 50 socioeconomic variables (level of education, income, children per family, major economic activity, use of conservation practices, etc.). Around 500 households, distributed all over the watershed, were visited, interviewed and GPS-located. A multivariate statistical analysis allowed an exploratory analysis to eliminate non useful and redundant variables and then to determine what variables appear to be important predictors of deforestation

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behavior among rural families. A resulting logistic regression model showed that household with lower annual income heads and with less use of conservation practices were more statistically prone to clear the forest ($\alpha = 0.001$). The study uncovered the complexity of this problem and confirmed the need of using GIS–remote sensing techniques to combine socioeconomic and environmental data in several time–space dimensions to find the causes and trends of tropical deforestation.

**Keywords** Deforestation · Tropics · Tropical rain forest · GIS–remote sensing · Logistic regression · Poverty

**Resumen** Los bosques tropicales están desapareciendo a un ritmo alarmante. En América Central, una hectárea de bosque es deforestada con fines agrícolas cada cinco minutos. Este estudio se realizó en una cuenca forestal de 4.000 hectáreas en el centro de Honduras con el objetivo de encontrar las causas de deforestación basado en las características socioeconómicas de la población. En primer lugar, un análisis multitemporal de imágenes Landsat TM se llevó a cabo para determinar las tasas de deforestación y las fronteras agrícolas-forestales. Un procedimiento búfer de Sistemas de Información Geográficos, SIG permitió determinar que los hogares estaban en *el frente* la deforestación y que los hogares se encuentra en el resto de la zona (de control). Las técnicas de SIG se utilizaron para extraer la información biofísica como la pendiente, la altitud, la cobertura del suelo, temperatura, precipitación, etc. Se estableció una base de datos con más de 50 variables socioeconómicas (nivel de educación, ingresos, niños por familia, importancia económica la actividad principal, el uso de prácticas de conservación, etc.). Alrededor de 500 familias, repartidas por toda la cuenca, fueron visitadas, se entrevistaron y se ubicó su posición con un Sistema de Posicionamiento Global (GPS). Un análisis estadístico multivariado permitió un análisis exploratorio para eliminar las variables irrelevantes y redundantes y luego determinar qué variables parecían ser predictoras importantes del comportamiento de la deforestación de las familias rurales. Un modelo resultante de regresión logística mostró que los hogares con menores ingresos anuales y con un menor uso de prácticas de conservación fueron estadísticamente más propensos a cortar el bosque ($\alpha = 0{,}001$). El estudio puso de manifiesto la complejidad de este problema y confirmó la necesidad de la utilización de los SIG, de las técnicas de teledetección para combinar los datos socioeconómicos y ambientales en varias dimensiones de espacio-tiempo para encontrar las causas y tendencias de la deforestación tropical.

**Palabras claves** Deforestación · Bosque tropical · SIG y Teledetección · Landsat · Regresión logística · Pobreza

## Introduction

Deforestation rates in the tropics are reaching alarming dimensions. According to FAO (2005), forest area continued to decline in Central and South America, with the leading cause of deforestation being the conversion of forest land to agriculture and pasture. The largest percentage loss of forest area continued to take place in Central America, although the rate has fallen in this sub region since 2000. From 25.7 million hectares of forest in 1990 in Central America, only 21.9 millions remained in 2000 and 19.5 in 2010. The annual change rate was for the first decade of −1.56 % while it decreased to −1.19 % in the later one (FAO 2005). This rate is not only the greatest of Latin America, but the greatest of the world, only comparable to the one of West Africa for the same period (−1.12 %). At a national level Honduras presents also the highest rate of deforestation for the period 2000–2010 of Central America (−2.1 %) only comparable to the 2.0 % of Nicaragua. In Honduras, alone, a hectare of forest is cleared for agriculture every 5 min (Rivera et al. 1999; Rivera 2004).

Forests in Honduras are being depleted at an accelerated rate. The deforestation rate is currently 80,000 hectares per year (Rivera et al. 2011b, c), which is one of the highest deforestation rates in the hemisphere (FAO 2005). Fertile and productive land is scarce, forcing small farmers to migrate and cultivate on steep hillsides. The disruption of environmental equilibriums is reflected by problems in agriculture, water management, marine resources, wildlife, and human health. This phenomenon holds serious consequences for the environment, such as loss of soil fertility, soil erosion, river channel sedimentation, reduction of hydroelectric power, reduction of habitat for wildlife, deteriorating drinking water quality, increasing floods, etc.

This vicious circle of poverty-environment deterioration is one of the key drivers of human migrations to more developed regions (World Bank 2000). Around 60 % of the population still lives under the poverty line and are willing to migrate to more prosperous areas. The United States (87 % of migrants) and Canada are the most preferred destinations for migrants (García 2006). Human immigration has had several peaks in the last decades; in the 80s, motivated by the political instability of the region, at the end of the 90s due to the devastating destruction of Hurricane Mitch and in 2009, due to the political instability of the country (Meyer 2011). Today, it is being increased by the struggling economy and the alarming crime and unemployment rates.

Remittances play a role in spurring this migration and it has become the country's largest source of revenues. Between 2002 and 2008, remittances from the US to Honduras tripled to $2.7 billion, the equivalent of 20 % of GDP (Meyer 2011). These funds sent from migrants abroad finance enhanced access to education and medicine and, consequently, greater urbanization. They also have allowed more families in some areas to purchase tracts of land, pushing up real estate prices and exacerbating existing land scarcity problems that contribute to migration. Clearly, remittances have become an integral feature of Central American economies in the past decade, and play increasingly activist roles in shaping the rural communities.

Local government agencies are struggling to find sustainable ways to concentrate farmers' activities in one area and reduce migrations. In order to implement such plans, substantial technology improvements is necessary, so that farmers can improve production and productivity (Pascual 2005). One solution to minimize erosion and deforestation rates is to stabilize farmers in one site and promote implementation and adoption—over the long term—of conservation measures (Hellin and Schrader 2003). To date, these measures have not been adopted, due mainly to farmers' lack of knowledge of the economic value lost via erosion, the lack of diffusion of the advantages of soil conservation tool adoption, and the lack of incentives to avoid soil loss (Lutz et al. 1994). At the end, agencies require that conservation measures need to be adopted and implemented permanently. We nonetheless acknowledge that this is not the sole alternative to prevent deforestation and erosion, and that incentive policies may be detrimental to sustainability.

This article makes a new step and in linking deforestation causes and developing a GIS spatial model that combines a watershed's biophysical characteristics (location of features) and social analysis (education, income, land tenure, etc.) of all its inhabitants. The analyses were conducted to understand the differences between households located in areas that were deforested versus households located at areas with persistent forest (control). This study integrates statistical and GIS–remote sensing capabilities to assess biophysical and social conditions in the Calan river watershed, in the central mountains of Honduras.

## Characterization of the Study Area

### Characterization of Honduras

Honduras, located in the middle of Central America, has an area of 112,088 square kilometres and a population of 5.8 million people (World Bank 2000) (Fig. 1). Approximately 46 % of the country is still covered by forests (Rivera et al. 2011b; Humphrey 1997) and the rest is being used for agricultural and cattle ranching. The climate is characterized by having a long wet season in the north and a long semiarid season in the South. Precipitations are irregular, originated form the Northeast winds. The annual mean temperature varies from 22 to 24 °C (Hargreaves 1992). The climate consists of a dry season (higher temperature values occur from March to April) and a rainy season (higher temperature values occur from May to December) (Hirt et al. 1989). Rainfall in the valleys is approximately 1,200 mm per year, while upland forest-covered areas receive an annual average of 2,000 mm (Hirt et al. 1989). High intensity rainfalls due to hurricanes can be anticipated once in 3–4 years.

### Characterization of the Calan Basin Study Area

The study watershed is located within the municipal boundaries of Siguatepeque (Fig. 1). This watershed is the source of drinking water for its population and a downstream population of 80,000 people. The studied watershed is a typical first-order one located in central Honduras (Fig. 1). This population is entirely rural and the vast majority lives below the poverty limit. The population density is around 80 people per square kilometre and is increasing at 3 % per year, which means that the population is likely to double during the next 23 years.

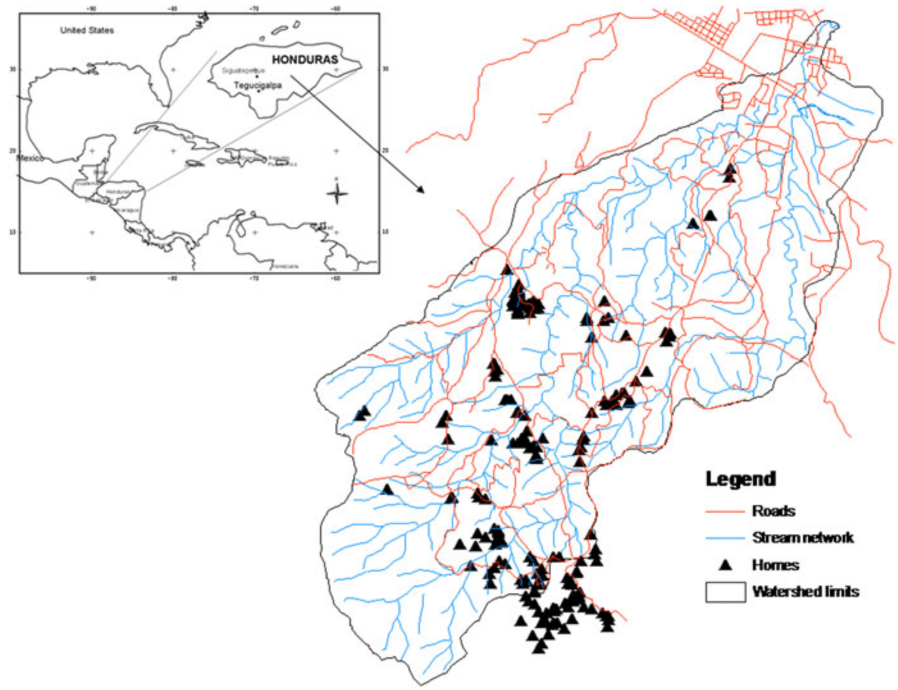


**Fig. 1** Location of Rio Calan watershed located in the Central Mountains of Siguatepeque, Honduras

The landscape topography of the watershed is rugged. Tributaries are generally enclosed in narrow V-shaped valleys and possess a dendritic drainage pattern. Watersheds' area average 42.6 ha and their elevation ranges between 720 and 1,960 masl. Watershed's average slope is 33 %. Soils of the upper watershed which originated from limestone are fertile. Soils of the medium and lower watershed which originated from clay stone are much less fertile. Only small valleys in the lower watershed have alluvial fertile soils. Most of these soils have slow water percolation, especially in the upland areas, leading to more surface runoff (Hargreaves 1992).

Because of soil quality and rainfall, the upper part of the watershed is totally cultivated while the middle part is occupied by forest and a small valley in the lower watershed is mostly left for extensive pasture. Most of the farming consists of semi-subsistence farming. Because there is no easy access to public transportation, commercialization seems to be difficult. The crops are maize and beans, and coffee production is limited. Agriculture covers about one-third of the watershed area (Hernandez 1999).

The forest, which covers 65 % of the watershed, contains two types of trees: pine trees in the central part of the watersheds and broadleaf trees located mainly in the very upper part of the watershed. The pine trees are *Pinus oocarpa* specie, which is adequate for timber production, and *Pinus maximinoi*, that occurs in the upper elevations. The broadleaf trees are usually deciduous species of Oak (*Quercus* sp.). This oak is suitable only for fuel wood and fences (Hernandez 1999).

## Methodology

The methodology consisted in three main steps: field data collection (a), Remote sensing and GIS analysis (b) and the statistical analysis and model development (c).

### Field Data

The field data collection consisted of the establishment of data base containing information from a 100 % of the households of the watersheds. We used 1:20,000-scale aerial photographs (Fig. 2) to spatially identify the 525 household locations and conduct the daily work planning of the field crews. Around 20 senior students of

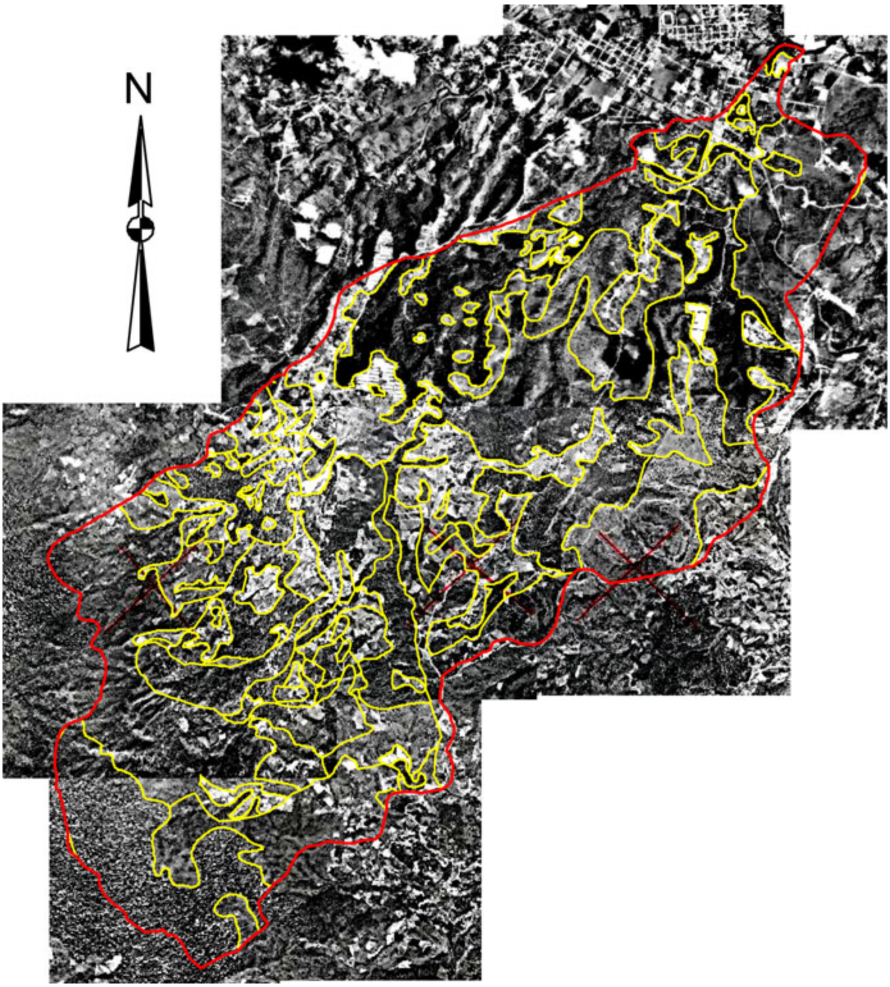


**Fig. 2** The photointerpretation of a mosaic of aerial photographs (scale 1–20,000) provided the basis for a preliminary land use classification and the location of households

the National School of Forest Sciences (ESNACIFOR) conducted a questionnaire with 75 questions related to agricultural, forestry and socioeconomic issues. We developed standardized field forms using MS Excel® and recorded GPS coordinates at each location to provide spatial correlation to the tabular data. Field data, including GPS coordinates (Fig. 1) and pictures were introduced in an MS Access® database which was established to organize, manipulate and manage the data. Field data acquisition occurred during the summer of 2002 and updated in 2005. We doubled checked, refined and standardized data, as a mean of quality controls for the data base management.

## Remote Sensing and GIS Analysis

For the land cover classification, we used two Landsat TM images: one scene from 1993 and another from 2000. We geometrically corrected and registered the Landsat data to a common UTM projection with an RMS error of less than 1.0 pixel. ERDAS Imagine® ver 9.3 was used to conduct a supervised classification, a method consisted on exploring the image and compute clusters that represent group of pixels with similar spectral properties. The classes of the map are developed according to reference areas, called *training areas* taken from field notes and high resolution data. We employed the 525 household GPS data as training samples for the supervised classification effort (Fig. 1). In addition, we used a mosaic of aerial photos for land use classification, as reference areas (Fig. 2). The software then characterized the statistical patterns and classified the image (Fig. 3). Both procedures were applied to both temporal scenes. Due to the Landsat sensor limitation of mapping coffee plantations that grow under the forest canopy, we decided to increase the field work. We manually delineated, using GPS units in the field, all coffee plantations showed in Fig. 4. Aerial photographs (scale 1–20,000) provided the basic information to conduct the field assessment and the daily work planning of the field crews. The other classes were relatively easily detectable in the images.

Due to the lack of geo-spatial data, we produced by manual digitization of the National Institute of Geography (IGN) 1:50,000-scale maps and the satellite images data, the following information: digital maps of soils, road networks, human settlements, and a digital elevation model generated from 10-m contour lines to create a slope map. Data layers were produced by clipping the study watershed boundaries into the classified images. Spatial data was manipulated using ArcGIS® 9.2, and socio-economic data was extracted (drilling) from each layer. The spatial analysis tool *Combine* function allowed us to overlapped the classified images and detect temporal changes. We identified deforested and non-deforested houses by "dropping" their locations over the land use change layer. We used them later for the logistic model development.

## Statistical Analysis and Model Development

We used spatial environmental variables and aggregate socioeconomic data (e.g., census data) in a discrete-choice (*logit*) model to estimate the probability that any

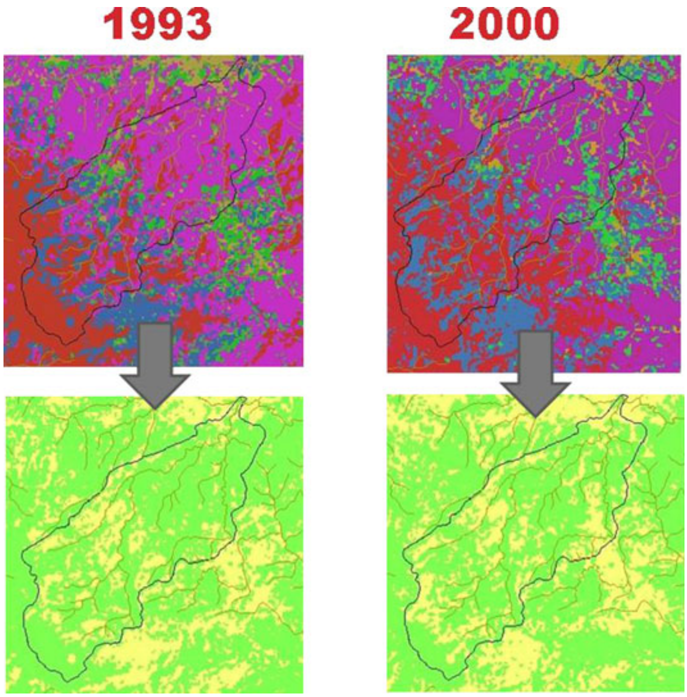


**Fig. 3** Supervised classifications of Landsat TM 1993 and 2000 images (*up*) derived the 1993 and 2000 maps (*below*) from the Calan River watershed showing a binary classification: forest (*green*) and non forest (*yellow*) classes. (Color figure online)

particular pixel in the landscape would be deforested, as a function of explanatory variables. We used a logistic regression model due to its ability to produce a dependent variable that is binary: yes (1) or no (0), rather than continuous (Ludeke et al. 1990). The presence of deforestation was considered a success or 1, and the absence of deforestation a failure or 0. Values in between denoted the probability of every pixel (30-m resolution) to be deforested for agriculture. This logistic model GLM (generalized linear model) was used to simulate the presence/absence of deforestation over the 4,000-ha watershed.

We selected variables that relate the most to deforestation behavior among rural families. The variables incorporated into the models were: (X) coordinate, (Y) coordinate, Annual income per family, Number of children per family, Adult literacy, Children literacy, Land ownership, Source of water, Septic tank-latrine, Cooking energy source, Agroforestry, Soil conservation practices, Vegetables, Fruit trees, Domestic animals, and Produce market.

We used the R software® ver, 2.7.0 to study potential relationships, linearity, normality and redundancy among variables and ArcGIS® ver. 9.2 to develop and extract the information from the "drilling" process in using the raster calculator function. The logistic regression model used was the Eq. 1:

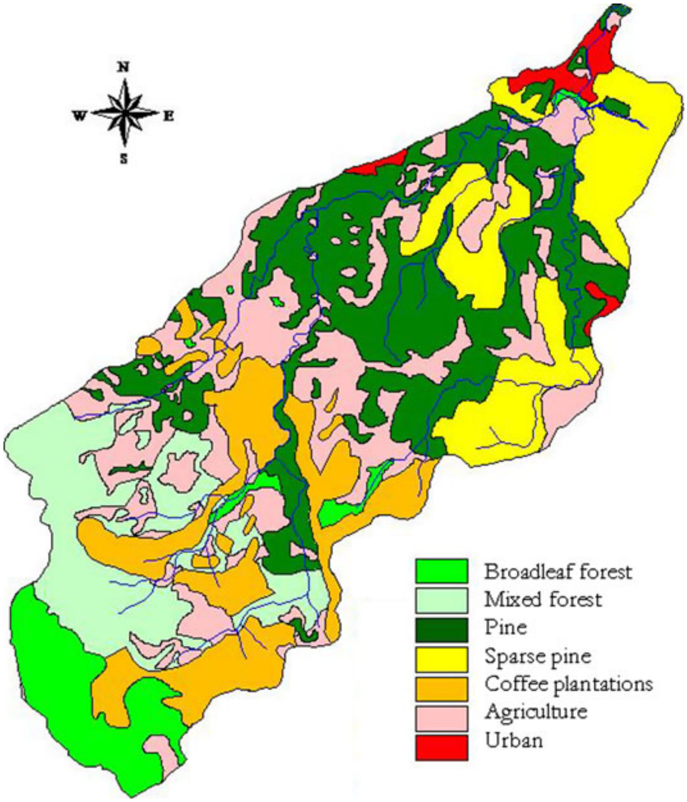


**Fig. 4** Land use and cover of the Calan River watershed in Siguatepeque, Honduras. A map derived from a 2000-Landsat TM image classification. Shade-tolerant coffee plantations were manually-GPS delineated in the field

$$P = \frac{\mathrm{e}^{\mathrm{a+bX}}}{1 + \mathrm{e}^{\mathrm{a+bX}}} \quad \text{or} \quad \frac{1}{1 + \mathrm{e}^{\beta 0 + \beta 1 * \mathrm{X1} + \beta 2 * \mathrm{X2} + \cdots + \beta \mathrm{k} * \mathrm{Xk}}} \tag{1}$$

where $\beta 0$ is a constant and $\beta \mathrm{i}$ are coefficients of the predictor variables. The computed value of $P$ is a probability between 0 and 1.

## Results and Discussion

Results are exposed according the following areas:

Land Use Classification and Multi-temporal Analysis

As a result of the image classification, a reduction in forest cover of about 20 % was observed between the period of 1993 and 2000 year (Fig. 3). These results revealed that forest cover is being destroyed rapidly especially in two locations as presented

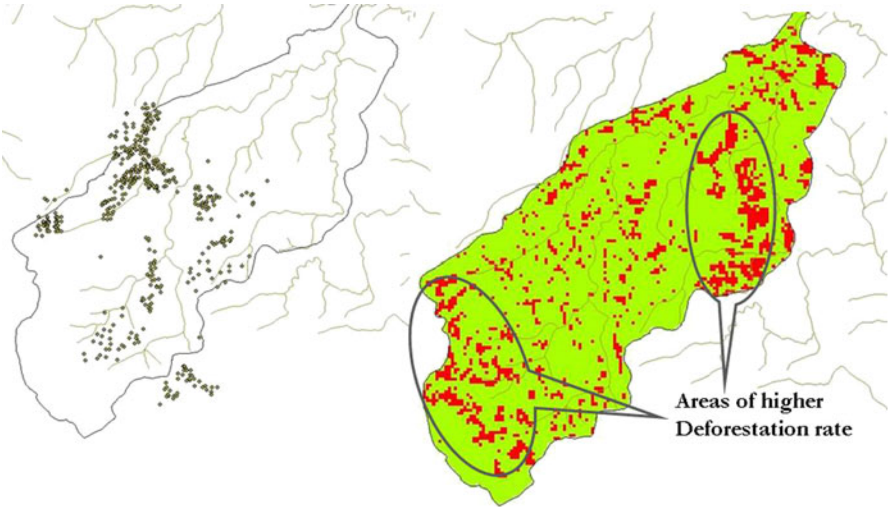


**Fig. 5** Map showing the household distribution (*left*) and the areas that were deforested (in *red*, in the right map) during the 1993–2000 period versus the areas with no change (in *green*, in the right map). It also shows the areas where most deforestation is occurring. About 20 % of forest was cleared. (Color figure online)

in Fig. 5, represent the areas of mayor concentration of deforested patches. They clearly show that there is an advance of deforestation from the east and from the west towards to the centroid of these areas.

Two distribution patterns tools were used to analyze deforestation: vector and fractal. Vector deforestation is occurring in these areas of higher deforestation rates. The deforestation process has direction and magnitude between the two dates based on the image classification (Kuzera et al. 2005). The direction of change indicated whether a landscape had experienced deforestation, or forest cover remained persistent. Magnitude indicated to what degree the change occurred. The vector deforestation is the pattern that can be observed in the *areas of higher deforestation* as shown in Fig. 5. The fractal deforestation is the *patchy* pattern that can be observed in the rest of the watershed (Fig. 5). This deforestation pattern has only an increase in area (magnitude) without a specific direction or advance front.

Vector deforestation, is occurring in areas less populated, as shown in Fig. 5. These areas are deforested following an agricultural front that has a direction and advance. It usually moves upward, from the lower elevation and flat areas to areas over the hills on higher elevations. Vector deforestation is occurring at a higher rate than fractal or patchy deforestation. The environmental damage is also larger, because more bare soil is being exposed to the effect of rain on higher slopes, producing more erosion and sedimentation (Rivera et al. 2011c). Because the loss of soil can no longer sustain profitable crops in the next 2–3 years, the farmers have to migrate further up in the hill to repeat the process. Although, it is not demonstrated in this study, vector deforestation usually is performed by larger colonizers, with more resources: labor and capital.

This study also provides both statistical and spatial confirmation of the importance of access in the location of deforestation. These findings have been made by other authors: (Lutz et al. 1994; Bravo-Ureta et al. 2006). Location of houses and shelters was shown to be spatially and statistically related to deforestation. Duncan (1978), in his case study of highland Honduras, found that most shifting cultivation sites were within 4 km from the cultivator's home. The descriptive statistics produced by this study confirmed Duncan's finding. Further, this study demonstrated that information on the socio-economic conditions of households provide strong prediction of families to promote deforestation practices.

## Model Findings and Predictions

The results showed that the spread of deforestation were statistically related to some variables. Annual income per family, the implementation of agroforestry, soil conservation and vegetable cropping practices resulted highly significant ($\alpha = 0.001$) as socioeconomic variables that most contributed to slow down deforestation among the non-deforestation households (Tables 1, 2). The implementation of fruit trees practices ($\alpha = 0.05$) and having domestic animals

**Table 1** List of model variables analyzed using a logistic regression model, Calan river Basin

| No. | Model variables | Description |
|---|---|---|
| 1 | (X) coordinate | How far East the household is located within the watershed |
| 2 | (Y) coordinate | How far North the household is located within the watershed |
| 3 | Annual income per family | Annual income of all residents over the age of 18 in each household |
| 4 | Number of children per family | Number of all children below the age of 18 |
| 5 | Adult literacy | Number of adults able to read and write |
| 6 | Children literacy | Number of children able to read and write |
| 7 | Land ownership | Household located at either national, municipal, tribal, or private land |
| 8 | Source of water | Household water use from either stream, well, or tap water |
| 9 | Septic tank-latrine | Presence or absence of septic tank |
| 10 | Cooking energy source | Electricity, propane gas or firewood |
| 11 | Agroforestry | Household head crops either coffee, cacao, cardamom or some other shade-tolerant crop species |
| 12 | Soil conservation practices | Household head implements conservation practices such as contour terrace, live and dead barriers, live fences and manure management |
| 13 | Vegetables | Household head crops: tomatoes, peppers or onions, mainly. |
| 14 | Fruit trees | Household head crops: avocados, critics, apples, mangoes, or other fruit tree species that represents a permanent tree cover |
| 15 | Domestic animals | Household head rises domestic animals such as: cattle, sheeps, pigs, and/or chickens |
| 16 | Produce market | Major produce' source of income is sold in local (distance <5 km), nearest town (distance <20 km) or capital city's markets (distance ~100 km) |

**Table 2** Model variables analyzed using a logistic regression model, Calan river Basin

| No. | Model variables | Statistical significance |
|---|---|---|
| 1 | (X) coordinate | NS |
| 2 | (Y) coordinate | NS |
| 3 | Annual income per family | ($\alpha$ = 0.001)*** |
| 4 | Number of children per family | NS |
| 5 | Adult literacy | NS |
| 6 | Children literacy | NS |
| 7 | Land ownership | NS |
| 8 | Source of water | NS |
| 9 | Septic tank-latrine | NS |
| 10 | Cooking energy source | NS |
| 11 | Agroforestry | ($\alpha$ = 0.001)*** |
| 12 | Soil conservation practices | ($\alpha$ = 0.001)*** |
| 13 | Vegetables | ($\alpha$ = 0.001)*** |
| 14 | Fruit trees | ($\alpha$ = 0.05)* |
| 15 | Domestic animals | ($\alpha$ = 0.01)** |
| 16 | Produce market | ($\alpha$ = 0.1). |

*NS* no statistically significant

. Significant at $\alpha = 0.1$ level

* Significant at $\alpha = 0.05$ level

** Significant at $\alpha = 0.001$ level

*** Significant at $\alpha = 0.0001$ level

($\alpha = 0.01$) also have a statistical significance among the non-deforested homes. Additionally, whether the excess produce is being traded: locally or transported to the nearest town, resulted also with statistical significance ($\alpha = 0.1$). The other variables described in Table 1 did to presented statistical significance when compared with deforested and non-deforested homes.

Some variables resulted irrelevant explaining the deforestation process. The estimated coefficients on the variables that measure the household location (X and Y coordinate within the watershed), household sized, children literacy, land ownership, source of domestic-use water, septic tank use, and energy source were not significant, meeting our a priori expectation. The estimated coefficients on household size and illiteracy were not statistically significant; the hypothesis was that these variables would increase the amount of land deforested because the understandable need to clear and crop land without little knowledge of conservation practices.

## Conclusions

According to these results, underlying causes of deforestation are related with low income population pressure (poverty deforestation according to Rudel and Roper

(1997) that require agricultural expansion. Economic reasons seem to be main driving cause of deforestation and it is caused by low-income families located at the deforestation front—upper watersheds—were they area prone to deforest and clear the forest as some authors have found in other areas (Humphries 1998; Godoy et al. 1998; Rivera et al. 2011a, c). In the Calan River, farmers decide not to increase deforestation when they earn bigger incomes, but also when they have implemented agroforestry, soil conservation and vegetable cropping practices, which are at the same time interrelated.

Given these results, it seems that conservation and local development policies should join efforts. Local government agencies are struggling to find ways to perpetuate and concentrate farmer's activities in one area and reduce migration to new forested areas to be cleared for agriculture. In order to implement this, substantial improvements of their technologies need to be applied, so they can improve production and productivity (Pascual 2005). A solution to minimize deforestation rates is to stabilize farmers in one site and promote the implementation and adoption—over the long term of conservation measures (Hellin and Schrader 2003). These results are consistent with many authors' findings that coincide that deforestation is an economic problem, that need to be solved at the rural family level that is affecting forested areas (Lutz et al. 1994; Bravo-Ureta et al. 2006).

In addition to the traditional wisdom about the deforestation problem, this study provides two important things. First, it identifies the type of management practices that government and local agencies should focus on providing technical assistance to rural families to lower deforestation rate. These practices are basically; soil conservation practices, fruit trees plantations, agroforestry, vegetable cropping, domestic animals (such as sheep and cattle) and providing means to trade their produce in the nearest urban town. Secondly, this study provides the spatial location of deforestation fronts where these practices or resources need to be applied to reduce the effect of deforestation. This is particularly important in a country where resources are limited. A more local GIS analysis can provide a more robust analysis of these deforestation causes linking them with direct drivers by understanding the choices that farmers make at their local level.

Extrapolating the study results to the country, agricultural and domestic animal management practices that increase the income at the level of rural homes may contribute to slow down the agricultural frontier forward moving into Central-American mountainous rainforest. In general providing mechanisms to improve a rural family income, has the benefit to lower the rate of deforestation practices.

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