

Understanding deforestation in montane and lowland forests of the Colombian Andes

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Abstract Colombian Andean forests cover nine million ha. These forests provide an informative case study of mountain deforestation in South America. They are surrounded by tropical lowland forests, and they host most of the country's human population. This study evaluates the relative importance of human and natural variables in deforestation of the Colombian Andes between 1985 and 2005 using remote sensing methods, geographic information system (GIS) technology and general linear models (GLM). The following factors affected the annual deforestation in the region positively: forced population migration, unsatisfied basic needs, economic activity, crops, pastures, illicit crops, protected areas and slope. Factors having a negative effect were tenure of small land parcels, road density, water scarcity and mean temperature. The results of this study also provide insight into the differences between the dynamics of lowland forests and those of montane forests. Montane forests had a lower annual rate of deforestation than did forests

in the lowlands. Socio-economic, demographic and biophysical factors explain overall deforestation rates for the region. However, when altitude variation is taken into account, intraregional differences in the Andes become evident. Deforestation processes differ between those areas adjacent to the high Andean valleys where most of the country's population concentrates and those areas in the tropical lowlands north, west and east of the Andean chain. Differences between lowland and montane forest dynamics are due partly to the accessibility of forests and differences in wealth and economic activities. In montane forests, deforestation is positively influenced by economic activity, the presence of protected areas and higher slopes. Deforestation in montane forests is negatively affected by tenure of small land parcels, road density, water scarcity and mean temperature. Lowland deforestation rates are more closely related to rural population, pasture percentage, crops, protected areas and temperature. Our results suggest that montane forests appear to be in a more advanced stage of colonisation and economic development, whereas lowland forests are closer to the colonisation frontier and to rapidly growing colonist populations. This study reinforces the idea that although the most common tropical drivers of deforestation are found in the Andes, these drivers operate differently when intraregional differences are considered.

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Introduction

Tropical forests are widely acknowledged as key systems for many aspects of life on earth, including not only environmental and ecological factors but also social,

cultural and economical components of human life (Wright 2005; Foley et al. 2007; Naidoo et al. 2008). However, recent estimates highlight the high percentage of CO₂ emissions that tropical deforestation contributes globally (Fearnside 2000; Achard et al. 2002; Santilli et al. 2004). Tropical deforestation is important to the global carbon cycle and it contributes to global change. Increasing awareness about the progress and consequences of tropical deforestation in recent decades has driven many researchers to understand what factors direct the course of this process. The majority of regional models of tropical deforestation that have been developed in recent years include a combination of economic, demographic, institutional, natural and policy factors that vary according to the spatial and temporal scale of the area studied (Brown and Pearce 1994; Geist and Lambin 2002; Rudel 2006; Kindermann et al. 2008). Recently, some authors have suggested that there are great temporal changes in the forces that drive tropical deforestation from old governments' rural settlement schemes to more enterprise-driven processes and current large-scale agricultural producers, such as large-scale soybean farming in Brazil (Rudel 2007; Vera-Díaz et al. 2008). The factors driving deforestation are often economically driven, and many of the current statistical models used are econometric models that use data at the municipal level (Dutra-Aguiar et al. 2007). Other attempts to model tropical deforestation have used artificial neural networks linking deforestation to selected environmental and socio-economic spatial variables such as elevation, slope, type of soil, distance from forests to roads or to settlements or spatial fragmentation (Mas et al. 2004). Some key studies during the last decade (Geist and Lambin 2002; Rudel 2007; Butler and Laurance 2008) suggest that common deforestation patterns can still be found but a multiple factor approach should be evaluated and the variability of circumstances over time should also be considered when studying forest loss (Rudel 2007).

For decades, tropical deforestation studies have been carried out with an emphasis on lowland tropical forests. For example, most deforestation studies in South America have been centred in the Amazonian basin (Câmara et al. 2005; Fearnside 2005; Kirby et al. 2006; Foley et al. 2007; Malhi et al. 2008). However, mountain areas represent an important percentage of South America. The tropical Andes hotspot (identified by Myers et al. 2000) covers 1,258,000 km², and this area has rarely been considered in deforestation studies. Globally, mountain areas are considered an essential source of ecosystem services. For example, mountain areas influence the hydrological cycle, thus providing water to populations living in mountain areas as well as in lowland settlements (Gomez-Peralta et al. 2008). Mountains are often considered major centres of biological diversity and cultural diversity (Fjeldså et al.

1999). Tropical mountains, such as the Andes in South America, are of particular interest given their high vulnerability to global change (Bush et al. 2004), and Andean forests are particularly susceptible and highly vulnerable to climate change because of their location on steep slopes and because of their altitudinal and climatic gradients (Karmalkar et al. 2008). In addition to climate change, tropical mountains are subject to high pressure from other natural and anthropogenic drivers of change such as land use and land cover change, soil erosion, landslides and habitat destruction (Achard et al. 2002; Bush et al. 2004; Grau and Aide 2008).

In South America, the Andes are home to almost 40 million inhabitants and thereby have an important economic and ecological role. Historically, the underlying causes of forest loss in the Andes have been large-scale cattle ranching, agriculture and clearance for government planned settlement schemes (Etter et al. 2006; Grau and Aide 2008). More recently, forest has been replaced with illicit crops, especially in Colombia, Peru and Bolivia (Bradley and Millington 2008). Population pressure is also considered one of the most important pressures on forest change in the Andes. Population growth in mountainous areas exceeds the national average and tends to concentrate people along transportation routes. Recent studies relate deforestation to environmental, population and economic factors in the highland forests of Ecuador (Keese et al. 2007), Bolivia (Killeen and Solorzano 2008), Peru (Kintz et al. 2006) and Colombia (Etter et al. 2006). In contrast to the most recent factors that have driven the disappearance of lowland forests (Rudel et al. 2009), large enterprise-driven deforestation has been identified as a major driver of mountain forest deforestation in only a few cases, such as with dry tropical forests in Bolivia (Killeen and Solorzano 2008). Lowland tropical forests are historically different from mountain forests in terms of land use, demography and economic activities, both in their intensity and change rates. Large-scale (e.g., cattle ranching) and small-scale farming were historically the most significant drivers of deforestation in the Amazon. These farming activities resulted from favourable incentives received by cattle ranchers in the 1960s–1980s. More recently, the establishment of soy farming has become a land-demanding economic activity (Kirby et al. 2006; Rudel et al. 2009).

Colombian Andean forests cover over nine million ha and are a good case study within the South American mountain system due to their particular geographical location. Colombian Andean forests are connected to the Caribbean, the Pacific, the Orinoco and the Amazon basin areas of tropical lowland forests. This paper analyses the effect of both human-related and environmental forces driving deforestation in the Colombian Andes. As topographical differences have been largely ignored in attempts

to model deforestation processes, we also look into topographical differences to model deforestation processes in this region, focusing on how much the deforestation drivers (both natural and human activities) vary when taking into consideration altitude variations. Our aim was to detect whether there are intraregional differences in the Andes and how deforestation processes differ between those areas adjacent to the high Andean valleys where most of the country's population concentrates and those areas in the tropical lowlands, north, west and east of the Andean chain.

Materials and methods

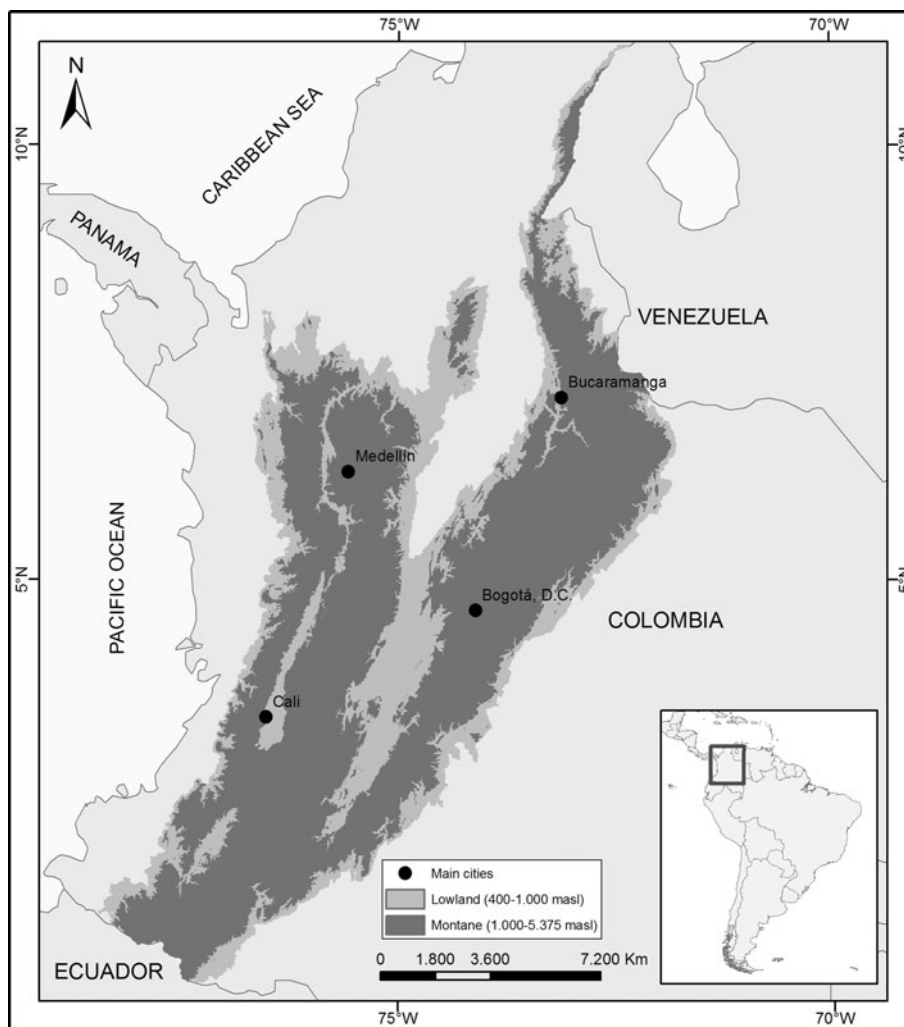
Study area

The Andes mountain range stretches from Chile to Venezuela for more than 8,000 km. It is a massive mountain range that influences many physical and biotic processes in South America (Ramos 1999; Braun et al. 2002). With an

area of nearly 8.1 million km² and peaks above 4,000 m, this cordillera (and specifically its tropical sector) has been repeatedly considered a global conservation priority because of its biological diversity, endemism and vulnerability (Mittermeier et al. 1999; Myers et al. 2000; Olson and Dinerstein 2002).

In Colombia, the Andes split into three cordilleras (Western, Central and Eastern) that surround the Magdalena-Cauca valley, which is one of the main watersheds of the country (Fig. 1). Even though the area of the Colombian Andes (287,720 km²; 400 m and above) only represents 25% of the total area of the country, 70% of Colombia's population is settled within the mountain range (Armenteras and Rodríguez 2007). The human occupation of the Colombian Andes dates back to pre-Hispanic times and has been increasing since the 1950s. This increase in montane areas is due to urbanisation processes and in lowland areas is associated with a migratory phenomenon resulting from the expansion of the colonisation front, leading to a substantial change in the natural landscape

Fig. 1 Study area



(Armenteras and Rodríguez 2007). Crops like coffee and potato, cattle pastures, illicit cultivation and urban development (Cavelier and Etter 1995; Armenteras et al. 2005) have affected the wide diversity of Colombia's Andean ecosystems. By 2000, only 39.5% of the natural cover remained (Rodríguez et al. 2006). Due to its exceptional diversity and vulnerability, a considerable number of protected areas have been established in the Colombian Andes. However, only 8.4% of the area is nationally protected (Morales 2007). Thus, the effective protection of mountain forests is not guaranteed (Armenteras et al. 2003).

Andean forest zonation is mainly defined by altitude because of its influence on temperature and orographic rainfall. A number of different classification systems have been used in South America (Holdridge, Grubb, UNESCO and IUCN), with each country adopting its own variation of one of these systems. Generally, low elevation rainforests (<900–1,000 m) are followed by montane forests (1,000–3,500 m). In a Colombian montane forest ecoregion study focused on the eastern flank of the Andes, Armenteras et al. (2003) adopted a zonification that differentiated sub-Andean montane forests (1,000–2,000 m) and Andean montane forests (2,000–3,500 m). For the purpose of this study, we established a 1,000 m elevation limit (Fig. 1) and considered all forests below 1000 m as lowland forests, including those that are near the Andean piedmont and lowland tropical areas such as the Amazonia, Orinoco and Pacific regions, and all forests above 1,000 m as montane forests.

Deforestation maps

Remote sensing data from over 70 Landsat multispectral satellite images using Multispectral Scanning (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) dated from 1985 and 2005 from a previous study were used (Rodríguez et al. 2006). The Landsat data were geometrically corrected and georeferenced to the Transverse Mercator projection, Datum Bogotá Observatorium, International Ellipsoid of 1909, latitude 4°35' 56.57"N; longitude 74°4' 51.3 W. This projection was used to integrate all variables into GIS. The best images for the construction of the 1985 and 2005 forest maps were used and interpreted at the scale of 1:250,000. Given the high cloud and shadow cover of some areas of the Andes, more than one scene was combined to generate the land cover map for both years with a total cloud and shadow cover below 7%. Furthermore, due to technical problems (banding) of Landsat after 2003, the 2005 land cover map was completed using SPOT and Aster imagery and deforestation spatial data provided by SIMCI (UNODC 2006). A mixed digital supervised classification with on-screen visual interpretation was carried out using ERDAS Imagine V8.7

software (Leica Geosystems 2005). Image interpretation was aided by detailed information from vegetation and soil cover maps that exist for some departments (IGAC-ICA 1985; IGAC-Corpoica 2002). Images were classified into the following major land cover classes according to their imagery spectral response as follows: forests (including dry forests), secondary vegetation (second growth vegetation of early and intermediate stages), agriculture, pastures and other (including eroded, forest plantations, urban areas and roads). To analyse the altitudinal differences in deforestation, two different classes of forest were created using the altitudinal line of 1,000 m, thus differentiating lowland and montane forests (Fig. 2).

A sequence of filters and data depuration were carried out. First, statistic filters were applied to the original cover to eliminate pixels that were misclassified. Next, a boundary clean function was performed to soften borders between different classified areas. A minimum mapping unit of 25 ha was used. Images were classified independently, and both post-classification field verification and statistical validation were performed. For the 2005 map, we used 372 verification points obtained from field data stratified according to the size of the polygons (Meidinger 2003) and available detailed land cover maps (IGAC 2002) for some regions and aerial photographs to obtain an overall global accuracy and Kappa coefficient of 90.4% (Rodríguez et al. 2006). For the 1985 map, we used secondary information from regional and local land use maps (IGAC-ICA 1985, IGAC-Corpoica 2002) for those 372 points, achieving an accuracy of 83.7%.

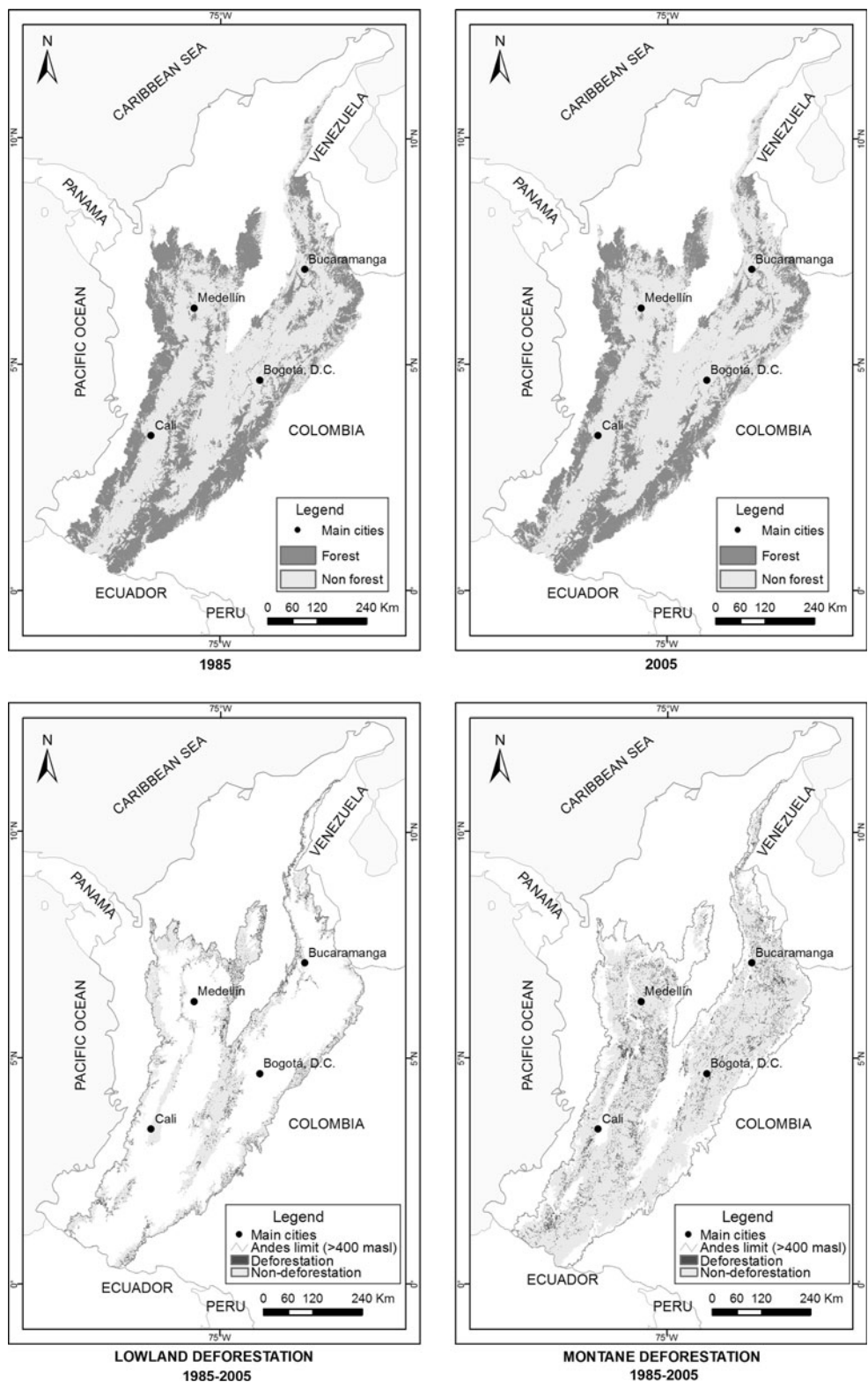
Forest maps for both periods were incorporated into GIS using ArcGIS. An overlaying analysis was performed to assess deforestation areas observed between the two periods analysed and locate sites where deforestation occurred. The analysis was focused on 627 municipalities in the Colombian Andes (only those that have more of 50% of their rural territory in the Andes region). Of these municipalities, 139 of them had lowland forest and 623 had montane forest. Deforestation rates for all forests, and then for both montane forests and lowland forests, were assessed based on the forest maps. Following Fearnside (1993), we computed deforestation rate (R , in %) within the Andes region as follows:

$$R = ((A_{1985} - A_{2005}) / (A_{1985} \times t)) \times 100$$

where A_{1985} and A_{2005} are forest areas in 1985 and 2005, respectively, and t is the time interval in years (in this study, the time interval was 20 years). We also computed R for each municipality. We considered montane and lowland forests separately.

For the statistical analysis of the effect of the different variables considered on deforestation at the municipal level, we weighted the size of the forests in a municipality

Fig. 2 Lowland and montane forests in 1985 and 2005 and deforestation hotspots between these dates



(otherwise municipalities with small forests would count as much as municipalities with large forests). We applied a factor derived from the contribution of the forest area within each municipality (A_{1985m}) with

respect to the total forest in the Andes region (A_{1985}) in 1985. From these considerations, we calculated each municipality's rate of deforestation contribution (R_m) to R as follows:

$$R_m = ((A_{1985m} - A_{2005m}) / (A_{1985} \times t)) \times 100$$

with $R = \sum R_m$.

Datasets used for independent variables

The analysis concentrated on the 627 forested municipalities of the Andes during the 1985–2005 period. The selected possible explanatory variables for deforestation at the regional level were demographic, socio-economic, land use and physical environmental variables (both abiotic and biotic). A GIS database of independent variables that could be considered as elements influencing deforestation in the region a priori was integrated using the municipality as the basic spatial analysis unit. Originally, there were 75 variables. We reduced this to 20 variables (Table 1) to avoid using highly correlated variables or variables with missing data.

Demographic and socio-economic data were obtained from the national population census at the municipal level from the National Administrative Department of Statistics. This dataset included data on literacy rates, unsatisfied basic needs (a commonly used composite indicator combining census level household measures such as access to adequate housing conditions, water, electricity and sanitation; Feres and Mancero 2001), quality of life, number of inhabitants (rural and urban) and forced migration. Most of the demographic and socio-economic data were obtained from the 1985, 1993 and 2005 population census (Departamento Administrativo Nacional de Estadística-DANE 1985, 1993, 2005). Digital maps of national protected areas, indigenous reserves, municipalities, road networks and human settlements were obtained from the Agustín Codazzi National Institute of Geography (IGAC 2005) at a scale of 1:500,000. IGAC also provided us with the digital elevation model based on the Shuttle Radar Topography Mission (SRTM, 90 m resolution) from which a slope map (in degrees) was derived. Climatic variables, such as mean annual temperature and annual precipitation, were derived from a climatic database of meteorological stations, interpolated and then summarised for the territory of each municipality (IDEAM 2006). We used spatial analysis techniques, including neighbourhood and distance calculations, map algebra and reclassification, to analyse physical environmental variables in GIS.

Statistical analyses

The comparison between annual deforestation rates per municipality of montane and lowland forests was carried out with a Student *t* test after log transformation of the data. A general linear model (GLM) was used to explore the relationships between deforestation and the different demographic (urban population, rural population, forced

population migration), socio-economic (small land parcels tenure, quality of life, literacy rates, economic activity, unsatisfied basic needs, energy consumption), land use (crops, pastures, illicit crops, coffee area, protected areas) and physical environment variables (road density, distance to nearest forest fragment, maximum slope, water scarcity in dry years, temperature, precipitation). We specified the three following different GLM models for deforestation: one for the total forest area (all forested area in the Andes without altitudinal differentiation), one for montane forests and one for lowland forests. All parameters were estimated by maximum likelihood, and given the high number of data in our analyses, significance was accepted at $p = 0.01$. To normalise the data, several variables (deforestation, water scarcity in dry years, urban population, rural population, economic activity, energy consumption, illicit crops, protected area, and distance to nearest forest fragment) were log-transformed. Statistical analyses were carried out using STATISTICA 6.0.

Results

Total forest in the whole study area decreased from 11,006,893 ha in 1985 to 9,528,961 ha in 2005 (0.67%), which represented a forest loss from 7,335,125 ha to 6,405,591 ha (0.63%) in montane forests and from 3,671,768 ha to 3,123,369 ha (0.75%) in lowland forests. In total, 616 out of 627 municipalities lost a variable proportion of their forests. Annual deforestation rates per municipality of montane and lowland forests were not significantly different (Fig. 3; Student *t* test, $p > 0.01$).

The best model of total deforestation ($R^2 = 0.55$, $p < 0.001$, $N = 627$) included the effects of four demographic and socio-economic variables (forced population migration, small land parcels tenure, unsatisfied basic needs and economic activity), four land use variables (crops, pastures, illicit crops and protected areas) and four physical environment variables (road density, maximum slope, water scarcity in dry years and mean temperature). In regard to the demographic and socio-economic variables included in the model, unsatisfied basic needs and forced population migration had a significant positive effect on deforestation, indicating that forest loss was higher in municipalities with high poverty and migration; economic activity also positively influenced deforestation, while deforestation increased in municipalities with lower proportion of small land parcels tenure. The four land use variables included in the model affected positively deforestation rate, which increased with the increment of crops, pastures and illicit crops and the presence of protected areas in the municipality. In regard to physical environment variables, deforestation rate increased significantly

Table 1 Summary of the variables considered in the deforestation analysis and dataset sources

Type	Short name	Units	Description	Source
Demographic	Urban population	Number of inhabitants	Absolute change of urban population between 1985 and 2005	National Administrative Department of Statistics (DANE) (1985, 1993, 2005)
	Rural population	Number of inhabitants	Absolute change of rural population between 1985 and 2005	National Administrative Department of Statistics (DANE) (1985, 1993, 2005)
	Forced population migration	Number of people	Number of people forced to leave their lands by illegal armed groups or displaced population	Consultoria para los Derechos humanos y el desplazamiento—(Codhes 2005a, b)
Socio-economic	Small land parcels tenure	%	Percentage of small land parcels tenure per municipality in 1995	Ministerio de Agricultura y Desarrollo Rural. Censo de minifundio en Colombia (1995)
	Quality of life	Unitless	Quality of life (ICV, Índice de Calidad de Vida) is a composite index with values between 0 and 100 that represent the minimum and maximum possible level of population quality of life, respectively. Includes information on education, family size, household building quality material, water availability, garbage collection, household density and income	Colombian National Planning Department (2003)
Land use	Literacy rates	% of population	Literacy rates per municipality	National Administrative Department of Statistics (DANE) (1985, 1993, 2005)
	Economic activity	Million Colombian pesos	Taxes revenues per municipality, equivalent to tax income in million Colombian pesos in 2005	National Planning Department (Departamento Nacional de Planeación-DNP, 2008) and the Unified Information System for (Sistema Único de Información de Servicios Públicos-SUI, 2008)
	Unsatisfied basic needs	%	% of population with unsatisfied basic needs in 2005. In Latin America, most countries consider as basic needs minimum household conditions, access to sanitary services, access to primary education and minimum economic capacity of the household	National Administrative Department of Statistics (DANE) (2005)
	Energy consumption	Kw/h	Municipality energy consumption in 2005	National Planning Department (Departamento Nacional de Planeación-DNP, 2008) and the Unified Information System for (Sistema Único de Información de Servicios Públicos-SUI, 2008)
	Crops	ha	Total change of crop area (in ha) between 1985 and 2005 derived from the satellite image classification	Calculated
Land use	Pastures	ha	Total change in ha of area under pastures	Calculated
	Illicit crops	ha	Area under coca (<i>Erythroxylum coca</i>) crops	United Nations Office on Drugs and Crime (UNDOC 2006), through the Colombian Integrated System for Illicit Crops Monitoring project or SIMCI (Sistema Integral de Monitoreo de Cultivos Ilícitos)
	Coffee Area	ha	Area under coffee in 2005	Colombian Coffee Federation (2005)
Land use	Protected area	ha	Area of each municipality under special management either under category of national protected area or indigenous reserve	IGAC (2005)
				Calculated

Table 1 continued

Type	Short name	Units	Description	Source
Physical environment	Road density	km/ha	Density of roads in km/ha was calculated also for each one of the municipalities	IGAC (2005) Calculated
	Distance to nearest forest fragment	Kilometres	Distance of the urban centre of each municipality to the nearest forest fragment existing in 1985 (in km) for all 3 forest types (montane, lowland, and total Andean)	Calculated based on forest map 1985 and urban centres provided by IGAC (2005)
	Maximum slope	Degrees	Maximum Slope (in degrees) for each municipality was calculated representing their average values for each municipality	Calculated (IGAC 2005)
	Water scarcity in dry years	%	Index of water scarcity in a dry year	IDEAM, Instituto de Estudios Ambientales y Meteorológicos (2000)
	Temperature	°C	Annual mean temperature	Calculated from climatic database
	Precipitation	Mm	Annual precipitation	Calculated from climatic database

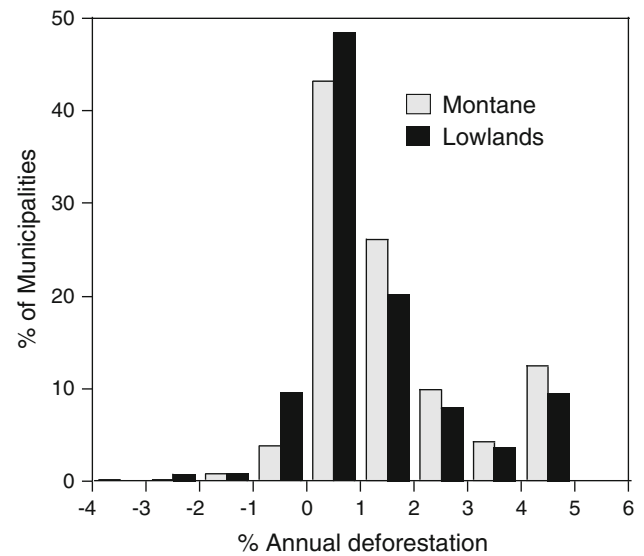


Fig. 3 Percentage of municipalities in the Andes with different rates of deforestation in **a** montane forests ($N = 623$, grey) **b** lowland forests ($N = 139$, black)

with mean temperature and water scarcity but declined with road density and maximum slope (Table 2A).

In the case of montane forests (Table 2B), the best model of deforestation ($R^2 = 0.38$, $p < 0.001$, $N = 623$) included the effects of two demographic and socio-economic variables (small land parcels tenure and economic activity), one land use variable (protected areas) and four physical environment variables (road density, maximum slope, water scarcity in dry years and mean temperature). In all cases, the effect of these variables on deforestation in highlands was similar to their effect on total deforestation (Table 2B).

The best model of deforestation in lowland forests ($R^2 = 0.67$, $p < 0.001$, $N = 139$) included the effects of one demographic variable (rural population), three land use variables (crops, pastures and protected areas) and one physical environment variable (mean temperature). Deforestation was positively related to the increment of all these five variables (Table 2C).

Discussion

People have lived in the Andes of South America for centuries, and the pressure that humans have exerted upon the natural resources can possibly be traced back to pre-Colombian civilisations. However, the degree of impact has been different across different regions of South America. In particular, the Colombian Andes deforestation rate of 0.67% is slightly higher than average reported rates for South American forests (0.38%, Achard et al. 2002, 0.6%; WCMC 2000). Overall, socio-economically important factors such as economic activity, population, roads

Table 2 General linear model for deforestation of (A) all forests, (B) montane forests and (C) lowland forests of Andean municipalities as a function of different demographic (urban population, rural population, forced population migration), socio-economic (small land parcel tenure, quality of life, literacy rates, economic activity, unsatisfied basic needs, energy consumption), land use (crops, pastures, illicit crops, coffee area, protected area) and physical environment variables (road density, distance to nearest forest fragment, maximum slope, water scarcity in dry years, temperature, precipitation)

(A) Variable	Total		
	<i>F</i>	<i>P</i>	Beta
Urban population	0.4	0.533	-0.026
Rural population	0.0	0.912	0.003
Forced population migration	19.3	<0.001	0.144
Small land parcels tenure	17.0	<0.001	-0.124
Quality of life	1.6	0.211	-0.073
Literacy rates	1.9	0.163	0.066
Economic activity	30.7	<0.001	0.285
Unsatisfied basic needs	8.8	0.003	0.138
Energy consumption	1.3	0.246	0.041
Crops	19.7	<0.001	0.134
Pastures	25.2	<0.001	0.148
Illicit crops	12.0	<0.001	0.127
Coffee area	1.6	0.196	0.037
Protected area	34.4	<0.001	0.195
Road density	13.6	<0.001	-0.130
Distance to nearest forest fragment	0.6	0.448	-0.021
Maximum slope	33.2	<0.001	0.170
Water scarcity in dry years	22.6	<0.001	-0.176
Mean temperature	10.0	0.002	-0.114
Annual precipitation	0.35	0.590	0.021

(B) Variable	Montane		
	<i>F</i>	<i>P</i>	Beta
Urban population	0.6	0.439	-0.038
Rural population	0.8	0.374	-0.034
Forced population migration	3.8	0.050	0.080
Small land parcels tenure	18.0	<0.001	-0.151
Quality of life	1.6	0.201	-0.088
Literacy rates	6.0	0.014	0.137
Economic activity	31.6	<0.001	0.341
Unsatisfied basic needs	4.5	0.033	0.117
Energy consumption	0.5	0.480	0.030
Crops	4.6	0.032	0.080
Pastures	3.4	0.064	0.065
Illicit crops	4.0	0.046	-0.086
Coffee area	2.3	0.125	0.051
Protected area	18.6.0	<0.001	0.169
Road density	6.8	0.009	-0.109
Distance to nearest forest fragment	2.6	0.101	0.070
Maximum slope	39.2	<0.001	0.218

Table 2 continued

(B) Variable	Montane		
	<i>F</i>	<i>P</i>	Beta
Water scarcity in dry years	17.6	<0.001	-0.188
Mean temperature	27.8	<0.001	-0.224
Annual precipitation	0.4	0.515	0.032

(C) Variable	Lowland		
	<i>F</i>	<i>P</i>	Beta
Urban population	4.5	0.036	-0.141
Rural population	6.7	0.009	0.179
Forced population migration	0.7	0.402	0.056
Small land parcels tenure	0.0	0.845	0.011
Quality of life	0.4	0.528	0.065
Literacy rates	0.2	0.629	0.041
Economic activity	5.5	0.020	0.173
Unsatisfied basic needs	1.3	0.254	0.101
Energy consumption	0.2	0.498	0.044
Crops	13.5	<0.001	0.225
Pastures	23.2	<0.001	0.308
Illicit crops	6.5	0.011	0.200
Coffee area	4.8	0.030	0.153
Protected area	9.8	0.002	0.228
Road density	4.2	0.041	-0.161
Distance to nearest forest fragment	1.8	0.180	-0.090
Maximum slope	2.7	0.102	0.098
Water scarcity in dry years	3.2	0.073	-0.143
Mean temperature	22.5	<0.001	0.373
Annual precipitation	3.4	0.068	-0.130

Significant values at $p < 0.05$ are in italic. $N = 627, 623$ and 139 municipalities, for the total, montane and lowland analyses, respectively

and the proximity to local markets have strongly affected deforestation processes across the tropics (Vance and Iovanna 2006; Rudel and Roper 1997; Etter et al. 2005). These factors also influence deforestation in the Andes. In general, the understanding of deforestation in the Andes region falls within two sets of theories of deforestation in the tropics, those that identify networks of entrepreneurs, companies and small farmers as the chief agents of deforestation and those that focus on growing populations of peasants and shifting cultivators (Rudel and Roper 1997). In wealthier Andean municipalities, economic activity and concentration of land tenure, rather than poverty, drives deforestation. Although the Andes are a highly transformed area of Colombia and over 60% of the range has already lost its natural coverage, the Andes are still in an economic or developmental stage of natural resource extraction (exploitation, settlement and deforestation). The

Andes are an economically active area with higher tax revenue incomes than the rest of Colombia, largely because of the intensive use of the territory, including land use change from forest to pastures and other agriculturally productive activities. This activity is also linked to transportation development that has made the territory more accessible. This increased accessibility might initially have caused deforestation in flat areas, which are adequate for agricultural activities and which have subsequently been transformed in order to support productive activities. Moreover, land tenure plays an essential role in the Andes. Concentration of land tenure (i.e., fewer small land parcels) has led to higher deforestation. However, inaccessible areas, where most forests are concentrated, have lower road density, steeper slopes and a tendency to attract illegal cropping. Inaccessible areas have higher deforestation rates. Historically, because access to these areas has always been difficult, the areas in question have harboured violent illegal groups and have consequently experienced higher forced population displacement rates. Higher unsatisfied basic needs are reflected in higher forced migrations (involuntary displacement of the population due to illegal armed groups). Such dissatisfaction and its consequences might lead in turn to a decline in economic activity of some areas and to a corresponding increase in pressures in those areas into which populations are forced to migrate. In turn, these changes lead to increases in pastures and in cropland. Environmental aspects of the Andes also help to explain the high deforestation rates we found. Specifically, lower temperatures and less water scarcity were associated with higher rates of deforestation, especially in montane forests close to paramos and near urban centres. The protected areas were positively associated with deforestation might reflect the fact that many protected areas are located in remote and less-accessible districts. Historically, this is indeed the case for many highland parks established in the Andes (Armenteras et al. 2003).

In addition to the general trend towards deforestation in the Andes of Colombia, local differences occur between lowland and montane forests within the region. These differences may be related to two of the traditional explanations of deforestation in the tropics (Rudel and Roper 1997) and may support the suggested curvilinear relationship between economic development and deforestation. Rudel and Roper (1997) presented these two traditional explanations. First, deforestation was associated with the very poorest areas. These populations had no opportunities other than those resulting from land clearing. Second, deforestation was related to changes in wealth that stimulate economic activities in peripheral areas. Changes in wealth also increase job creation and provision of services. When these changes occur, people move to urban areas, and permanent migrants sell or abandon their

properties (and thus concentrate land in the hands of fewer owners). Indeed, despite the fact that there is no significant difference in deforestation rates between lowland and montane forests, the explanatory factors differ. This circumstance is partly due to Colombian land use and settlement history. For centuries, land use was intensive in the mountains. However, beginning in the second half of the twentieth century, the colonisation frontier moved towards lowland areas in the Andean piedmont (Etter et al. 2008). This transition is especially evident in the Andes–Amazonia transition belt.

Higher economic activity, land concentration and centres of development are mainly associated with highlands. In highlands, different types of migratory processes inside the country and a dispersed network of medium-sized cities led to a conformation of cities known as the Andean trapeze. The Andean trapeze is made up of Bogota, Medellin, Cali and Bucaramanga. Together, these four cities comprise almost 75% of the population and of the economy of the country (Galvis 2001). Around these cities and their areas of influence, forest remnants are located mainly in remote areas (Rudel and Roper 1997). It is clear that most of the population in these montane areas is concentrated in the urban centres. This concentration is due in part to forced migration that has occurred in the last five decades. The migration has redirected attention towards other kinds of economic activities and has led to an abandonment of agricultural activity. The result is less pressure on forests (Rudel and Roper 1997). In highland areas, where better conditions for productive activities are usually found, deforestation occurred in the past due to land use changes, e.g., crop intensification. However, deforestation currently occurs in remote areas (i.e., less-accessible areas having steeper slopes). This finding coincides with previously proposed arguments that suggest that at some point, rates of tropical deforestation should decline because a smaller number of forest fragments become increasingly inaccessible in mountain locations (Myers 1993). Deforestation is pushed to the outskirts of the municipalities in those areas with less road density and higher, steeper slopes. Sometimes, deforestation is also associated with the presence of illegal armed groups or with buffer zones around protected areas that are often located in less accessible and remote districts. This result appears plausible because their lack of access to education gives the people in these areas no alternative to agricultural activities and farming. The absence of alternative economic opportunities in rural and remote areas leads people to exploit natural resources in the remote but still-available montane forest fragments.

The differences between montane and lowland deforestation rates can be further explained by the socio-economic and demographic activities that occur in the municipalities in each area. Montane areas are at a

relatively advanced stage of colonisation, economic development and resource availability. Lowland forests are located in the lower-elevation territories of Colombia and on the colonisation frontier. These areas might be more likely to include growing and mainly rural populations. The development of the colonisation frontier is usually driven by a process of natural resource extraction. The process begins when farmers clear the land. Land clearing is followed by the establishment of cattle grazing as the main economic activity. Therefore, pasture establishment is a clear indicator of colonisation and is followed by the establishment of crops. Higher deforestation rates are also found in the municipalities whose boundaries include recently declared protected areas. Establishment of these protected areas might reflect a positive political response to areas of forest remnants with high pressure. Of course, lowland areas of the Andes have important abiotic differences from highland areas, and the environment is an indirect driver of deforestation. During the initial stages of deforestation (exploitation and establishment of cattle grazing or agriculture), colonists tend to go to available sites that offer the most comfortable environmental conditions. In the lowland Andes, the comfortable areas are those with higher temperatures, along the border of the Amazonian, Pacific and Orinoquian tropical rain forests. Deforestation in lowland forests in Colombia is likely to continue, given the relatively high availability of land in this transition zone. Additionally, lowland forests are becoming increasingly accessible and provide adequate environmental conditions for the cultivation of intensive crops such as yucca, maize and sugar cane that are cultivated mainly for biofuel production.

Conclusion

Most models of deforestation do not take into account altitudinal differences. Our study reveals that in mountain areas, this difference might have an important and largely ignored role. The nature of the proposed explanations for deforestation in the Andes and the intraregional differences between montane and lowland forests highlight the need to rethink development planning in the Colombian Andes and allows us to suggest planning and management strategies for these territories. Montane forests can further be preserved by increasing conservation initiatives at all levels and also by the promotion of agroforestry and other types of social forestry practices in rural highland areas of the Andes where most of the population lives. The colonisation front towards the lowland in the Andes, where the highest deforestation rate is currently found, has to be tackled with strong political action through planning schemes that avoid the establishment of settlements and roads in key

connectivity areas that could potentially be irreplaceable. Moreover, management should also integrate more rural development plans in already settled or recently settled places and reduce the development of areas with intact large forest fragments.

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