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# Land use and land cover change in the Colombian Andes: dynamics and future scenarios

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Land use and land cover changes (LUCC) are recognized as one of the most relevant drivers of biodiversity loss in ecosystems. Through the analysis of satellite images, this article quantifies the LUCC that occurred between 1985 and 2008 in the Colombian Andes. Four submodels of changes were analyzed: deforestation, crop intensification, conversion to pastures, and abandonment. We associated these changes with demographic, socioeconomic, and abiotic variables and to some attractors of landscape change, and finally we have considered three scenarios of change: reference, increase in pasture, and crop intensification. The dynamics of LUCC were dominated by systematic transitions between crops, pastures, and secondary vegetation. Of all the submodels, pasture conversion has an important contribution in terms of accuracy rate (84%), and the most relevant variables for explaining land cover changes in the region were elevation, soil type, and distance to roads, cities, and pastures. Our simulations suggest that the pasture conversion scenario would have the biggest impact in natural ecosystems and could cause the loss of 28–30% of the cover area by 2050. The results indicate some that these hotspots of change are currently still under a good conservation state with large extension of forests.

**Keywords:** land cover change; deforestation; land change modeler; drivers of change; scenario land use; South America

## Introduction

It is widely accepted that land use and land cover changes (LUCC) have an important effect on both the functioning of the Earth's systems as a whole (Lambin *et al*. 2001) and the majority of ecosystems (Hansen *et al*. 2001; Duraiappah *et al*. 2005; IPCC 2007a). Almost 15–20% of the $CO_2$ emissions on a global scale are due to the expansion of agricultural lands and pastures (IPCC 2000), and it is projected that by 2050 almost 80% of species extinctions will be caused by changes in land cover (mainly deforestation) in the tropical forests and savannas (Sala *et al*. 2000, 2005). LUCC also affect climate change in the long term. Many feedback processes exist between LUCC and the biogeochemical and biophysical processes of the Earth's system, including greenhouse gas emissions, ecological and physiologic processes, and modification of albedo (Foley, Heil Costa, Delire, Ramankutty, and Snyder 2003; Brovkin *et al*. 2006; Heistermann, Muller, and Ronneberger

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2006). LUCC also affect the conservation of essential ecosystem services that maintain the well being of humans on our planet (Manandhar, Inakwu, and Pontius 2010).

In the last several decades, land use changes in tropical forests have increased, and the human footprint in these ecosystems is the largest ever recorded (Asner, Rudel, Rudel, DeFries, and Emerson 2009). The conversion of forests to livestock pastures has been identified as a continuous process in Latin America (Wassenaar *et al*. 2007; UNEP 2007), similar to the conversion of other natural ecosystems such as savannas to pastures and cropland as a result of the growing world demand for cereals and oils. These activities cause biodiversity loss and modify climate patterns or hydrological cycles, but they are seen as an economic opportunity for local populations because they generate new markets for international trade (Rudel, DeFries, Asner, and Laurence 2009).

Mountain areas are especially vulnerable to global change (Bush, Silman, and Urrego 2004), and current studies on the effects of climate change and LUCC in these regions have identified detrimental impacts on ecological and social processes (Beniston 2003; IPCC 2007b). Some studies of LUCC in this region have focused on observing local causes of LUCC, evaluating their effects on environmental services and making predictions based on different scenarios of global change (Brandt and Townsend 2006; Etter, McAlpine, Wilson, Phinn, and Possingham 2006; Martínez *et al*. 2009). The development of future scenarios for land use and change should not only include the spatial and temporal patterns of this change but should also help in the planning and sustainable use of the resources of many tropical countries (Veldkamp and Lambin 2001). It is important to develop regional models and predictions of change for tropical mountain areas because of their vulnerability to climate change and the strong human influences present (Brandt and Townsend 2006). Despite the fact that mountain areas in the Andes have supported intensive traditional agriculture for centuries (Sarmiento 2000), human population growth and economic activity are still factors associated with the deforestation of highlands in many Andean countries (Kintz, Young, and Crews-Meyer 2006; Keese, Mastin, and Yun 2007; Armenteras, Rodríguez, Retana, and Morales 2011).

The Andes region, as one of the most populated areas in Latin America, contains more than 100 ecosystem types, 45,000 species of vascular plants (20,000 of them endemic), and 3400 species of vertebrates. The region is considered a high global priority for the conservation of biodiversity (Myers 1998). A fundamental obstacle in the studies of LUCC for the Andes has been the lack of spatially explicit regional analyses. The objective of this investigation is to undertake a regional analysis from 1985 to 2000 of LUCC in the Colombian Andes and to explore scenarios of future land use change to 2050. Specifically, this study focuses on (i) quantifying the dynamics and determining the spatial and temporal trends of LUCC, (ii) identifying the main transitions among land covers (i.e., submodels) and their associated drivers and attractors, and (iii) making projections about regional LUCC under different scenarios proposed by the International Panel on Climate Change (IPCC) until 2050.

### *Study area*

The Colombian Andes region encompasses 287,720 km$^2$ and is an area of great biological, cultural, social, and economic complexity. The region is included within the Northern Andes ecoregion, which is considered to be among the world's top 200 high-priority places for conservation because of its biological richness and vulnerability to human activities (Mittermeier, Myers, and Mittermeier 1999). The region extends along three mountain ranges: western, central, and east, with an elevation range between 500 and 5400 m asl.

Temperature distribution is related to elevation, with mean annual values of 26–28°C in lowlands, 13–14°C at 2500 m asl, and 0°C at 4800–5000 m asl. The distribution of rainfall is influenced by the Intertropical Convergence Zone: the eastern Andes are exposed to trade winds, which create humid and rainy conditions (annual precipitation values of ∼5000 mm); in the western region (Pacific slope), a Monzonic circulation system produces even more rain (annual precipitation above 5000 mm, with values of 12,000–13,000 mm in some sectors); finally, the inter-Andean valleys are less humid (annual rainfall of 1000–3000 mm).

Historically, the region has hosted intense human activity. Humans have occupied the Colombian Andes since at least 13,000 BP (Van der Hammen 1992). Etter and Van Wyngaarden (2000) and Etter, McAlpine, and Possingham (2008) found that the Andean ecosystems, along with dry ecosystems, have been those mostly affected by LUCC since the 1500s. The main drivers of change have been population expansion and intense human activities. In 2000, only 39.5% of the region had natural ecosystems (Rodríguez, Armenteras, Morales, and Romero 2006), including lowland forests, montane forests, paramos, and several highly degraded dry enclaves.

This region is characterized by being the center of economic activity of Colombia and contains most of its population (77.4%). The economy of the region mainly depends on the industrial sector, followed by agriculture. Coffee is an important agricultural product along with other crops, such as corn, potato, rice, sugarcane, and vegetables. In the 1980s–1990s, the number of cattle in the region increased due to increased availability of pastures. Land tenure is predominantly concentrated in farms smaller than 10 ha. In this region there are 30 natural parks, which encompass 9% of the total Andean region.

## Methods

### *Land use and cover changes*

The analysis within this study was based on LUCC maps obtained by classifying 52 Landsat TM and ETM images for the period 1984–1986 (year of reference, 1985) and 1999–2001 (year of reference, 2000) (Rodríguez *et al*. 2006). The images were co-registered with Landsat ETM images from 2000, orthorectified by the Geographical Institute Agustín Codazzi (IGAC), with quadratic mean errors smaller than the pixel size. Magna Sirgas was used as a reference system. The preparation and classification of the images was carried out with Erdas Imagine software V. 9.1. The images were classified using a mixed method (both supervised and unsupervised). In some cases, it was necessary to eliminate clouds and shadows by creating masks and using complementary satellite images for these areas. The percentage of clouds was smaller than 7%. An evaluation of accuracy was undertaken using the methodology proposed by Meidinger (2003). Through stratified sampling based on the proportion of land cover categories, we selected 372 points at random in the study area and then we verified these points from field data (from 2003 to 2004) and checked aerial photographs, SPOT images, and information from national and departmental agricultural censuses (Sistema Nacional de Información Agropecuaria, Federación Nacional de Cafeteros). Using the kappa coefficient, we found that the map from 2000 had an accuracy of 90.4%, while the map from 1985 had an accuracy of 83.7%. In addition, we calculated the total disagreement in terms of quantity and allocation, according to the recommendations proposed by Pontius and Millones (in press). The quantity disagreement was 9% and 19% and the allocation disagreement was 21% and 13% for the maps 1985 and 2000, respectively.

The analyses were carried out using the Land Change Modeler (LCM) version for Idrisi Taiga 9. This program, developed by Clark Labs at Clark University (2006), contains tools for land cover change analysis, and allows users to map changes in the landscape, identify land class transitions and trends, and model and predict the environment to create future landscape scenarios that integrate user-specified drivers of change. We analyzed LUCC among seven categories: montane forest (forest between 1000 and 3200 m asl), lowland forest (forest between 500 and 1000 m asl), paramo (shrub and natural grassland), grassland, annual and permanent crops, secondary vegetation (vegetation in different successional stages), and other (including forest plantations, water bodies, urban areas, bare soil, and snow). Cell size was 100 × 100 m. LUCC were evaluated using the transition matrix (the row totals indicate LUCC by category in 1985 and column totals indicate LUCC by category in 2000) through gains and losses, net change (expressed as the difference between gains and losses), persistence (expressed as the permanence of each cover between 1985 and 2000), swap change (expressed as the total change minus the net change for the category), and specific transitions between categories. We evaluated systematic process of transitions in the region using the methodology made by Alo and Pontius (2008). This systematic transition was based on deviations between the transitions observed and the transitions expected owing to random processes of change (Pontius, Shusas, and McEachern 2004; Manandhar *et al*. 2010).

The annual rate of change (rt) for each cover category was calculated as (Puyravaud 2003):

$$\mathrm{rt} = \frac{1}{(t_2 - t_1)} \times \mathrm{Ln}\left(\frac{A_2}{A_1}\right) \times 100$$

where $A_1$ and $A_2$ are the areas (in ha) of a cover class at years $t_1$ (initial time) and $t_2$ (next time step), respectively.

We identified LUCC hotspots using the map of changes in the period 1985–2000. Considering both surface and neighborhood, we analyzed the deforestation hotspots, which are areas with the highest changes from natural cover types (i.e., forests and paramos) to pastures and agricultural areas.

### *Transition submodels and drivers of change*

We worked four submodels for the region using a multi-layer perceptron (MLP), which is based on neural network. By default, the accuracy rate reported by MLP is supported on a leave 50% out rule. The submodels were the following (Figure 1):

(1) Deforestation submodel: conversion from forests to pastures and crops; within this model we separated the deforestation associated to lowland and montane forests.
(2) Agricultural intensification submodel: increase in agricultural activity due to the conversion of secondary land and pastures to crops.
(3) Abandonment submodel: change from agricultural areas to secondary vegetation.
(4) Pasture conversion submodel: change from secondary vegetation to pastures.

For each submodel, we considered 20 variables that have previously been reported as possible factors driving LUCC (Armenteras *et al*. 2011), including demographic, socioeconomic, physical and land use variables, and attractors of change such as distance to fires,

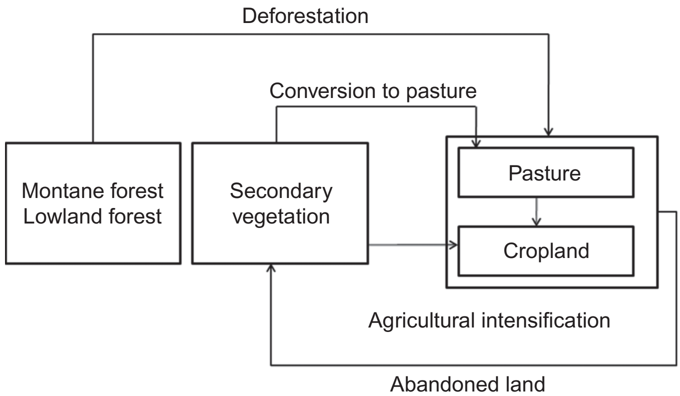


Figure 1. Land use and cover transition in Colombian Andes.

roads, cities, forests, and pastures (Table 1). As MLP requires continuous quantitative variables, we transformed the data of categorical variables using evidence likelihood that is an effective way to incorporate them into the analysis. We used the Cramer's V statistic to test the explanatory power of each variable and select the most relevant ones for each submodel (Eastman 2007). Once these variables were selected, each submodel was modeled using MLP. They were considered static components due to the extreme computational complexity for processing them as dynamics.

### *Prediction of land use and cover changes and scenarios of change*

We predicted LUCC based on the results obtained from the submodel transitions and the analysis of Markov chains, using the year 2000 as the reference date. LCM offers two types of models of change: hard and soft prediction models (Eastman 2007). In this study, we used the soft prediction model since it offers a more comprehensive assessment of change potential; it also yields a map of vulnerability to change and it is preferred for habitat and biodiversity assessments (Eastman 2007). To validate the models, we used the methodology proposed by different authors (Pontius *et al*. 2008; Pontius, Peethambaram, and Castella 2011) consisting in comparing three maps: the reference map of 2000, the reference map of 2008 (map obtained by the IGAC), and the prediction map of 2008. The three-map comparison allows us to distinguish the 2008 agreement due to land persistence versus the 2008 agreement due to land change and gives four types of results: correct due to observed persistence predicted as persistence (i.e., correct rejections), error due to observed persistence predicted as change (i.e., false alarms), observed changes predicted correctly as change (i.e., hits), and finally, error due to observed change predicted as persistence (i.e., misses).

Once we had the calibrated and validated model, we developed three scenarios of change for the period between 2020 and 2050, with the purpose of exploring regional and global impacts on natural ecosystems: (i) reference scenario (RES) where our assumption was that the current pattern of change will follow the same Markov's dynamics found for the region during the period 1985–2000, (ii) increase in pastures scenario (IPS), where there will be an increase in the number of cattle pastures, and (iii) crop intensification scenario (CIS), where there will be an intensification of cropland. These latter two scenarios

Table 1. Summary of the characteristics and origin of the datasets for the variables considered in the LUCC analysis.

| Type | Name | Units | Description | Source |
|---|---|---|---|---|
| Demographic | Total population (Pob) | Number of inhabitants | Absolute change of rural population between 1985 and 2005 | National Administrative Department of Statistics (DANE) (1985 y 2005) |
| | Forced population migration (Desp) | Number of people | Natural logarithm of number of people forced to leave their lands by illegal armed groups or displaced population | Consultoria para los Derechos humanos y el desplazamiento-Codhes (2005) |
| Socioeconomic | Economic activity (Ecac) | 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, 2005) and the Unified Information System for (Sistema Único de Información de Servicios Públicos-SUI 2005) |
| | Unsatisfied basic needs (Nbi) | % | Population with unsatisfied basic needs in 2005; unsatisfied basic needs is 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) | National Administrative Department of Statistics (DANE) (2005) |
| | Mineria (Mi) | ha | Area of mineral concessions | Calculated from map of mineral concessions. Unidad de Planeación Minero Energética (UPME) (2005) |
| Land use | Protected area (PA) | ha | Area under special management either under category of national protected area or indigenous reserve | Agustin Codazzi National Institute of Geography (IGAC) (2005) |

| | | | | |
|---|---|---|---|---|
| | Private reserve (PR) | ha | Area private under special management for conservation | Resnatur (2000) |
| | Change 1985–2000 (CH8500) | ha | Likelihood of total change of area between 1985 and 2000 derived from the satellite image classification | Calculated from Maps of land cover and land use 1985 and 2000 |
| Physical environment | Digital elevation model (DEM) | m asl | Altitude values | The Shuttle Radar Topography Misión (SRTM, 90 m resolution) |
| | Soil drainage (Soildrain) | Type of drainage | Likelihood of measures aiming at controlling a high water table and water logging in the land | IGAC and CORPOICA (2002) |
| | Soil fertility (EL_solifert) | Types of fertility | Likelihood of the quality of a soil that enables it to provide essential chemical elements | IGAC and CORPOICA (2002) |
| | Type of soil (EL_Soils) | Kind of soil | Likelihood of type of soil based on USDA classification | IGAC and CORPOICA (2002) |
| | Slope (Slope) | % | Likelihood to diverge from the vertical or horizontal | Data derived from DEM |
| | Depth of soil (Soildepth) | cm | Likelihood of depth of soil | IGAC and CORPOICA (2002) |
| | Precipitation (Prec) | mm | Annual precipitation | Calculated from CIAT database (2000) |
| Attractors | Distance to cities (Dist_cabec) | km | Distance to urban and suburban center existing in the region | Calculated based on human settlements map provided by IGAC (2005) |
| | Distance to focus of fire (Dist_fire) | km | Distance to hotspot fire between 2000 and 2002 | Calculated based Map of urban center provided by IGAC (2005) |
| | Distance to nearest forest fragment (Dist_forest) | km | Distance to forest existing in 1985 | Calculated based on Maps of land use and land cover, 1985 |
| | Distance to nearest pasture (Dist_pasture) | km | Distance to pasture existing in 1985 | Calculated based on Maps of land use and land cover, 1985 |
| | Distance to road (Dist_roads) | km | Distance to road existing in the region | Calculated based on road networks map provided by IGAC (2005) |

were based on the IMAGE model (Integrated Model to Asses Global Environment, version 2.2), used to implement the IPCC-MESSRS scenarios (IMAGE 2001), which assumes that there will be an increase in food production to satisfy the growing demand of human populations, favoring the expansion of pastures for livestock and arable lands at the expense of natural ecosystems (Bouwman, Van Der Hoek, and Van Drecht 2006).

## Results

### *Land use and cover changes*

Overall persistence between 1985 and 2000 for the region was 67.4% and 7.6% of the changed area due to an absolute value of net change (Table 2). Secondary vegetation and pasture are the most dynamic categories in terms of gains (11%) and losses (6.8% and 13%, respectively), while pasture showed a net change of 1.6% in the region and swapping change about 23%. Forests and paramos had persistence values over 84% and low proportion of swapping component of change (<1%), while the rate of forest loss (deforestation) was −0.83%, representing 1.5 million ha of forest lost within the area for the period 1985–2000. The greatest degree of change in lowland forests (deforestation hotspots) was located in the intersection of the Andes with the Amazonia, Orinoquia, and Serranía of San Lucas region. In the case of montane forests, the East mountain range was the most affected area (Figure 2). Loss of paramos was concentrated in the East Mountain Range (Boyacá and Cundinamarca Departments).

The transition matrix between 1985 and 2000 (Table 3) shows that forests and pastures were the main land cover types in the Colombian Andes, representing 65.2% of the total area in 2000. The two land cover categories that increased from 1985 to 2000 were crops (3.3%) and secondary vegetation (4.3%). Area of pastures decreased slightly from 1985 to 2000, but they were still the dominant land use in the region. Expansion of pastures occurred mainly in the south and the north of the region while pasture loss was distributed uniformly over the entire region (Figure 3a). The areas that showed an increase in agricultural activities were associated with the Magdalena Valley in the Eastern Mountain Range and Central Mountain Range (Figure 3b). The gains in secondary vegetation were concentrated in three places: the lower part of the Colombian Macizo (Central Mountain Range), the north of Antioquia (Central and West Mountain Range), and the high region of the Eastern Mountain Range (Figure 3c). The cross tabulation (gross gains and gross losses

Table 2. Transition budget as a percent (%) of study area in different categories of land use between 1985 and 2000. Total change indicates the sum between gain and loss for each category.

| Category/land cover class | Persistence | Gain | Loss | Total change | Swap | Absolute value net change | Loss rate annual |
|---|---|---|---|---|---|---|---|
| PA | 4.2 | 0.1 | 0.6 | 0.6 | 0.2 | 0.5 | −0.6 |
| MF | 22.2 | 0.5 | 3.3 | 3.8 | 0.9 | 2.9 | −0.8 |
| LF | 10.9 | 0.2 | 1.8 | 2.0 | 0.5 | 1.6 | −0.9 |
| SV | 5.9 | 11.1 | 6.8 | 17.9 | 13.6 | 4.3 | 1.9 |
| PS | 19.9 | 11.4 | 13.0 | 24.3 | 22.8 | 1.6 | −0.3 |
| CR | 3.3 | 8.3 | 5.0 | 13.3 | 10.0 | 3.3 | 2.2 |
| Other | 1.0 | 1.1 | 2.2 | 3.3 | 2.2 | 1.1 | −3.3 |
| Total | 67.4 | 32.6 | 32.6 | 32.7 | 25.1 | 7.6 | |

Note: PA, Páramo; MF, montane forest; LF, lowland forest; SV, secondary vegetation; PS, pasture; CR, crops.

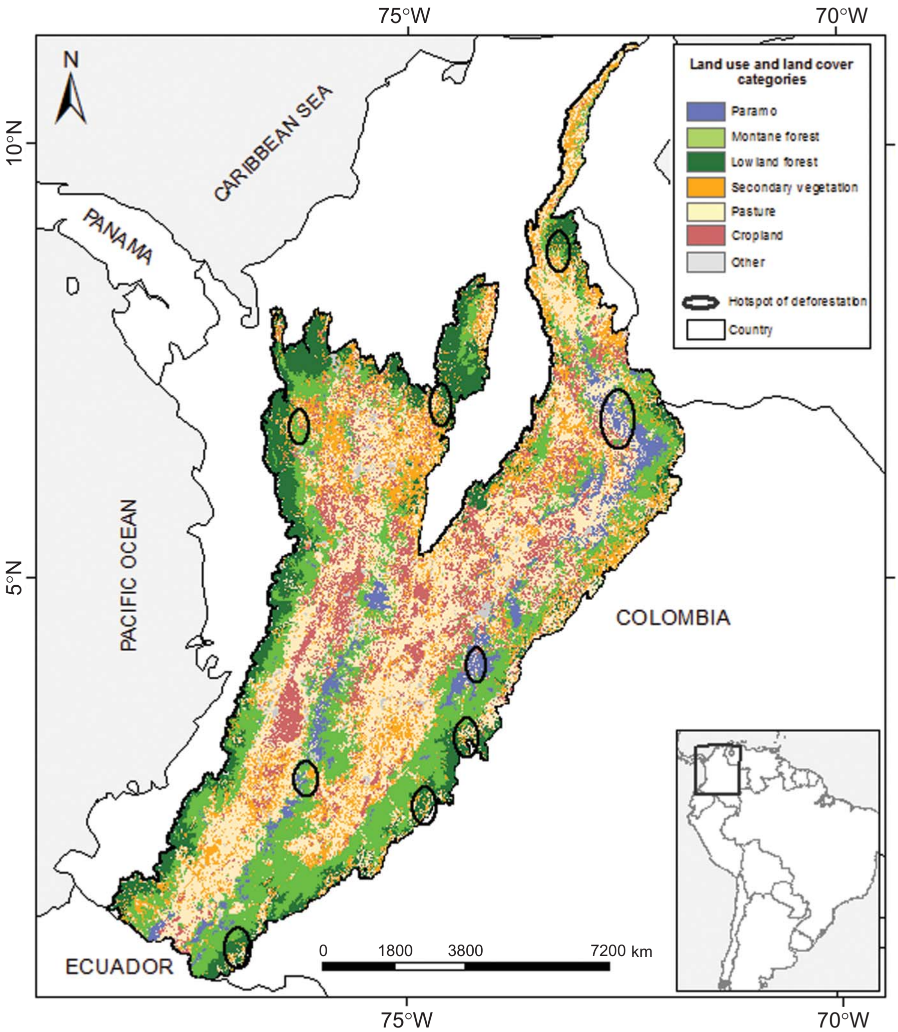


Figure 2. Land cover map of the Colombian Andes (year 2000) and identifications of hotspot of deforestation (between 1985 and 2000).

by category) identified important exchanges of areas between secondary vegetation and pasture (6.1%) and also cropland and pasture (5.8%).

Table 3 indicates that the observed gains are bigger than the expected gains for pasture to secondary vegetation, pasture to cropland, cropland to secondary, cropland to pasture, and secondary vegetation to pasture. Cropland, pasture, and secondary vegetation represent the dynamics of LUCC in the Colombian Andes and showed systematic process of transitions in the region; it means there is a tendency of systematic interchange between these categories. In other words, there is a systematic transition from pasture to cropland. Cropland was systematically gaining from pasture and at the same time pasture was also systematically losing to cropland. For forest categories (montane and lowland) observed gains were about the same as the expected gains in relation to pasture and secondary vegetation, thus there is not evidence of a systematic process.

Table 3. Transition matrix in the Andean region showing the percentage of the total category observed (in bold), random process of gain (in italics), and random process of loss (in normal font).

| | 2000 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1985 | PA | MF | LF | SV | PS | CR | Other | Total 1985 | Loss |
| PA | **4.2** | **0.0** | **0.0** | **0.0** | **0.5** | **0.0** | **0.0** | **4.8** | **0.6** |
| | | 0.0 | 0.0 | 0.6 | 0.8 | 0.4 | 0.1 | 6.2 | *1.9* |
| | | 0.1 | 0.0 | 0.1 | 0.2 | 0.1 | 0.1 | 4.8 | 0.6 |
| MF | **0.0** | **22.2** | **0.0** | **1.6** | **1.3** | **0.3** | **0.1** | **25.6** | **3.3** |
| | 0.0 | | 0.1 | 3.2 | 4.3 | 2.3 | 0.3 | 32.5 | *10.3* |
| | 0.2 | | 0.5 | 0.7 | 1.4 | 0.5 | 0.1 | 25.6 | 3.3 |
| LF | **0.0** | **0.0** | **10.9** | **1.1** | **0.6** | **0.1** | **0.0** | **12.7** | **1.8** |
| | 0.0 | 0.1 | | 1.6 | 2.2 | 1.2 | 0.1 | 16.1 | *5.2* |
| | 0.0 | 0.5 | | 0.3 | 0.6 | 0.2 | 0.1 | 12.7 | 1.8 |
| SV | **0.0** | **0.1** | **0.1** | **5.9** | **4.6** | **1.8** | **0.2** | **12.7** | **6.8** |
| | 0.0 | 0.1 | 0.0 | | 2.2 | 1.1 | 0.1 | 9.4 | *3.6* |
| | 0.4 | 1.9 | 0.9 | | 2.6 | 0.9 | 0.2 | 12.7 | 6.8 |
| PS | **0.1** | **0.2** | **0.1** | **6.1** | **19.9** | **5.8** | **0.6** | **32.8** | **13.0** |
| | 0.0 | 0.2 | 0.1 | 4.2 | | 3.0 | 0.4 | 27.7 | *7.8* |
| | 0.8 | 4.3 | 2.1 | 3.2 | | 2.2 | 0.4 | 32.8 | 13.0 |
| CR | **0.0** | **0.0** | **0.0** | **1.5** | **3.3** | **3.3** | **0.1** | **8.3** | **5.0** |
| | 0.0 | 0.1 | 0.0 | 1.1 | 1.4 | | 0.1 | 5.9 | *2.6* |
| | 0.2 | 1.3 | 0.6 | 1.0 | 1.8 | | 0.1 | 8.3 | 5.0 |
| Other | **0.0** | **0.0** | **0.0** | **0.7** | **1.1** | **0.3** | **1.0** | **3.2** | **2.2** |
| | 0.0 | 0.0 | 0.0 | 0.4 | 0.5 | 0.3 | | 2.2 | 1.3 |
| | 0.1 | 0.5 | 0.3 | 0.4 | 0.7 | 0.3 | | 3.2 | 2.2 |
| **Total 2000** | **4.3** | **22.7** | **11.2** | **17.0** | **31.3** | **11.6** | **2.1** | **100.0** | **32.7** |
| | 4.3 | 22.7 | 11.2 | 17.0 | 31.3 | 11.6 | 2.1 | 100.0 | *32.7* |
| | 5.9 | 30.8 | 15.3 | 11.6 | 27.1 | 7.5 | 1.9 | 100.0 | 32.7 |
| **Gain** | **0.1** | **0.5** | **0.2** | **11.1** | **11.4** | **8.3** | **1.1** | **32.7** | |
| | 0.1 | 0.5 | 0.2 | 11.1 | 11.4 | 8.3 | 1.1 | *32.7* | |
| | 1.7 | 8.5 | 4.4 | 5.7 | 7.2 | 4.2 | 1.0 | 32.7 | |

Note: PA, Páramo; MF, montane forest; LF, lowland forest; SV, secondary vegetation; PS, pasture; CR, crops.

### *Transition submodels and drivers of change*

Table 4 describes the results of the different submodels and their main explanatory variables. The lowest accuracy rate (62.2%) was for the abandonment submodel and the largest value (84.0%) was for the pasture conversion submodel. Overall, the most relevant variables explaining LUCC in the region were elevation, land type, and distances to cities, roads, and pastures in 1985 (using the threshold of Cramer statistic $>0.15$). Variables such as mining, economic activity, unsatisfied basic needs, and private reservations were not significant in any submodel (all showed values of Cramer statistic $<0.15$). Seven variables were included in the two submodels of deforestation, with a different emphasis on each (Table 4). Deforestation dynamics were strongly affected by all attractors of change, although distance to roads was not significant in the lowlands submodel. For the montane forest model, the most important factors affecting deforestation were distances to roads, cities, and pastures, while biophysical variables such as land type and precipitation mostly influenced lowland forests. Population displacement and the presence of protected areas were also significant in those submodels.

The pasture conversion submodel was explained by five variables, with precipitation and elevation being the most relevant ones (Table 4). In this submodel, as the proximity

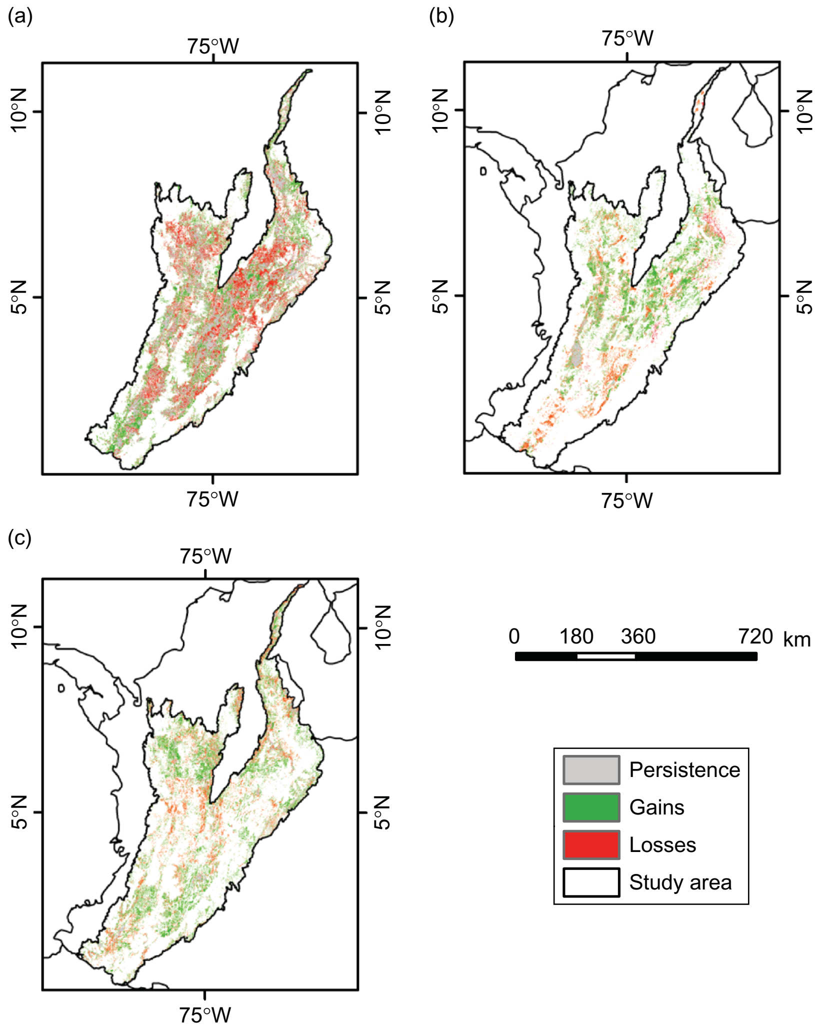


Figure 3. Map of gains, losses, and persistence of (a) pasture, (b) cropland, (c) secondary vegetation from 1985 to 2000.

to areas with pastures in 1985 increased, so did its probability of being transformed into cattle pastures. The submodel of agricultural intensification was related to physical environment factors (elevation, soils, and slope). Proximity to highways and populated centers emerged as the main drivers of economic development and commercialization of agricultural products in the region. In the submodel of abandonment, an important variable was forced population migration, which was also included in the deforestation submodel.

## *Scenarios of change*

For the validation of the simulated change from 2000 to 2008, the percent of the landscape consists of 0.4 hits, 1.7 false alarms, and 11.5 misses. Thus, the observed change was 11.9% of the landscape while the simulated change was 2.1% of the landscape, so most of

Table 4. Summary of the results for the goodness of fit of the calibration of the neural net in the LCM for the five transition models.

| Model | Principal factors | Accuracy rate | Training RMS | Testing RMS |
|---|---|---|---|---|
| Deforestation of montane forest | Dist_pasture, Dist_cabec, Dist_road, Dist_forest, EL_soil, Dist_fire, EL_PA, LnDesp, Pecip | 75.5 | 0.4151 | 0.4138 |
| Deforestation of lowland forest | EL_soil, Prec, Dist_pasture, EL_PA, EL_soilfert, LnDesp, Dist_cabec, Dist_forest | 74.3 | 0.4239 | 0.4138 |
| Agricultural intensification | DEM, EL_soil, Dist_forest, Dist_pasture, Dist_road, Dist_cabec, Dist_fire, EL_slope | 67.9 | 0.4532 | 0.4531 |
| Pasture conversion | Prec, DEM, EL_soil, Dist_pasture, Dist_fire | 84.0 | 0.2507 | 0.2511 |
| Abandoned land | DEM, EL_soil, Dist_road, Dist_cabec, EL_slope, LnDesp | 62.2 | 0.3375 | 0.3377 |

Note: Forced population migration (LnDesp), protected area (PA), soil fertility (EL_solifert), type of soil (EL_soils), slope (EL_slope), precipitation (Prec), distance to cities (Dist_cabec), distance to focus of fire (Dist_fire), distance to nearest forest fragment (Dist_forest), distance to nearest pasture (Dist_pasture), and distance to road (Dist_roads). Accuracy rate indicates the ability to predict the submodel with the variables used.

Table 5. Percentage of each land cover area that changes in the three scenarios considered (2000 reference): RES (reference scenario), IPS (increase of pastures scenario), and CIS (crop intensification scenario).

| | RES | | IPS | | CIS | |
|---|---|---|---|---|---|---|
| | 2020 | 2050 | 2020 | 2050 | 2020 | 2050 |
| Montane forest | −5.6 | −15.6 | −16.3 | −28.3 | −9.8 | −20.2 |
| Lowland forest | −3.9 | −14.7 | −17.5 | −30.2 | −8.1 | −20.9 |
| Paramos | −6.4 | −15.0 | −8.0 | −15.0 | −8.0 | −14.0 |
| Secondary | −4.3 | −4.3 | 14.5 | 22.0 | −4.4 | −0.8 |

Note: Positive and negative values indicate increases or decreases in this land cover, respectively, for the corresponding date (either 2020 or 2050).

the error was due to simulation of less than the observed amount of change. The dynamics of LUCC in the Colombian Andes varied depending on the scenarios considered. Table 5 indicates the percentage of different natural land use areas that could change under each different scenario in 2020 and 2050. All scenarios, including the RES, showed considerable reduction in four land covers (montane forest, lowland forest, paramos, and secondary vegetation) and increase in pastures. The changes are generally the greatest in IPS and the lowest in the RES (Figure 4). Concerning spatial patterns, most part of the affected area under these scenarios will be the Eastern Mountain Range (Figure 5).

The pasture expansion (IPS) scenario had the biggest impact on forests, with losses between 16% and 30%. A similar, albeit lesser, reduction in forest areas was obtained

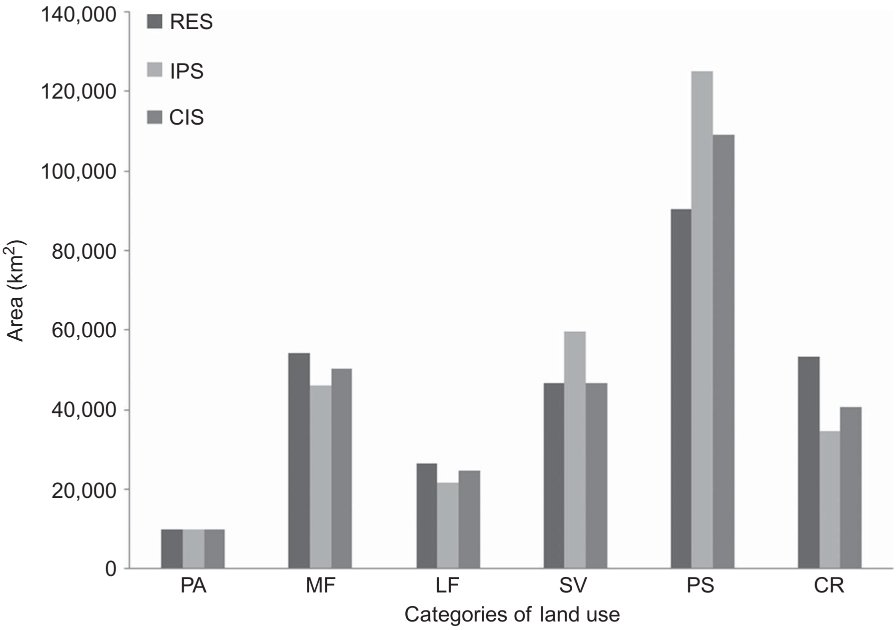


Figure 4. Area (km$^2$) of different categories of land use in each scenario for the year 2050.
Notes: PA, Páramo; MF, montane forest; LF, lowland forest; SV, secondary vegetation; PS, pasture; CR, crops.

using the CIS. Paramos showed similar losses in all three scenarios, with the changes concentrated in the Eastern Mountain Range (complex of paramos of Pisba and Cocuy). Losing these high mountain ecosystems could have strong implications for the water supply of the main cities in the region. Under the first and third scenarios (RES and CIS), secondary vegetation was projected to decrease by 4% in 2020, and by a similar or lower value in 2050 (Table 5). In the second scenario (IPS), there was a considerable gain in secondary vegetation due to abandoned cattle lands (14% in 2020 and 22% in 2050). This turnover was expected to occur in the lowland areas of Andes, limited by the lowland forests of the Pacific and Amazonia (Figure 5).

## Discussion

### *Patterns of land use and cover change*

Recent studies have found that tropical forests are mostly affected by LUCC (Mayaux *et al*. 2005; Lambin and Geist 2006; CDB 2010). In Latin America, LUCC displays two patterns: deforestation caused by rising global food demand and increasing numbers of cattle, and the abandonment of agricultural lands, favoring the recovery of ecosystems (UNEP 2010). Our results indicate that the Colombian Andes, despite having a history of land use from before Prehispanic times, still has almost 38% of its natural ecosystems in the year 2000, even though the deforestation rate is high compared with other countries in South America (Achard *et al*. 2002). A high percentage of forests have remained unchanged between 1985 and 2000 and the highest deforestation hotspots in the region are located in lowland forests, which is consistent with studies by Wassenaar *et al*. (2007), Etter *et al*. (2006),

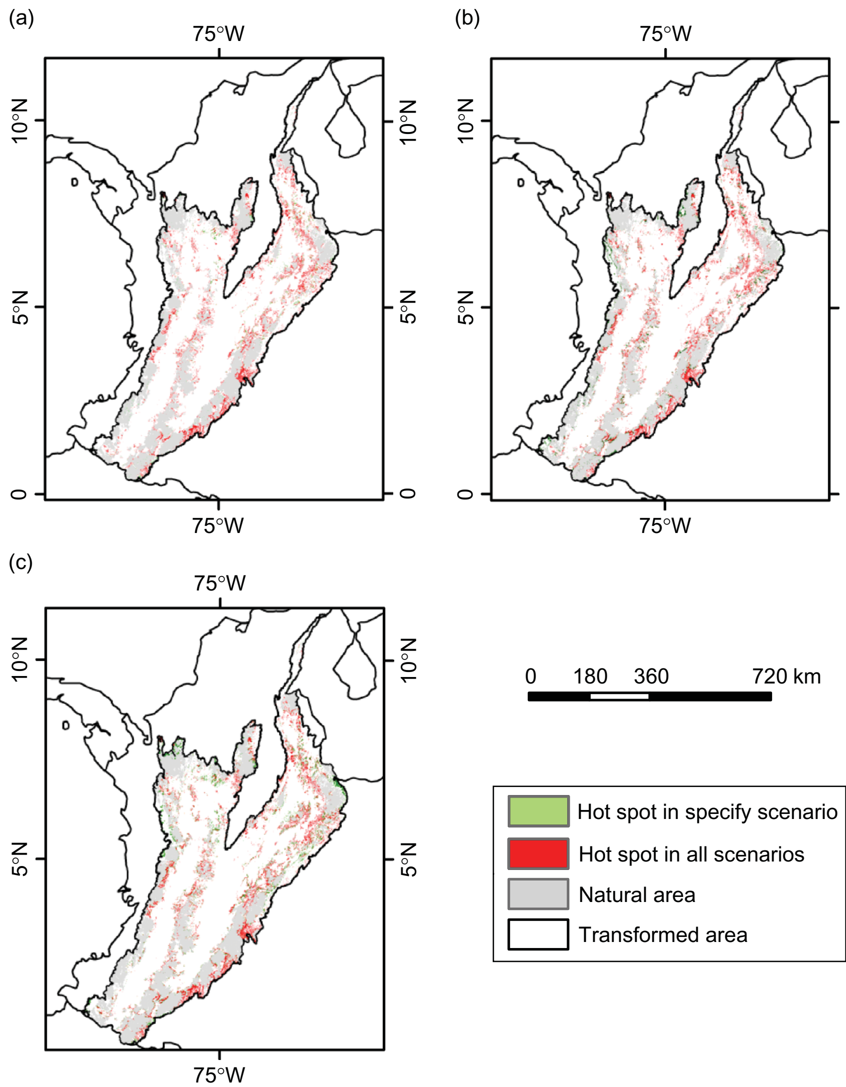


Figure 5. Identification of hotspots of deforestation for 2050 (a) RES (reference scenario), (b) IPS (increase in pastures scenario), and (c) CIS (crop intensification scenario) in the Colombian Andes. The gray color indicates natural areas and white color indicates nonnatural areas.

and Armenteras *et al*. (2011). These studies identified critical points of deforestation in the Napo region along the Ecuadorean border, the lowland forests of the East Mountain Range, and the forests surrounding the San Lucas Mountains (West Mountain Range). These hotspots are associated with cattle expansion and subsistence agriculture that are adapted to prevailing environmental conditions (high precipitation and high slopes) and, in the West Mountain Range, to mining activity, mainly gold production (Orrego 2009). The East Mountain Range and the Magdalena Valley are the most affected montane forest areas, where deforestation is associated with agricultural expansion. These processes have negative implications for conservation because these ecosystems are considered hotspots of biodiversity (Myers 1998).

In addition to this deforestation process, there is also a net gain of secondary vegetation, which is consistent with the trends found in other tropical mountain areas (Gómez, Vega, Ramírez, Palacio, and Galicia 2006; Flamenco-Sandoval, Martínez-Ramos, and Masera 2007; Redo, Joby Bass and Millington 2009). Secondary vegetation has become an important element of the Andean landscape in recent years, and its increase has been generally associated with areas of forest recovery after continuous selective logging. Secondary vegetation originating from these processes is located in edge areas between the Andes and the low areas of the Amazonia and Magdalena Medio (Figure 2). This fact is consistent with the statement outlined by Rudel, Bates, and Machinguiashi (2002) that transition forests are generated by emigration. There is also an increase of secondary vegetation due to the abandonment of agricultural areas, although in these cases there is no definitive abandonment of crops but only temporal transition to pasture land.

The replacement of natural cover types by pastures is a historical pattern of land use and change in the Andean region, where livestock is an important socioeconomic element. Its expansion is associated with the concentration of large areas to attain resources and to obtain political and economic control (Van Ausdal 2009). Mahecha, Gallego, and Peláez (2002) state that the expansion of the agricultural frontier and the establishment of pastures in Colombia have been delayed in areas with sociopolitical conflicts (as in the transition zones between Pacific, Andes, and Amazon where this expansion is associated with secondary vegetation), while livestock has promoted the economy in areas with high income and employment rates (as in the inner part of the Andes, where it is associated with a model of pasture conversion and agricultural intensification).

The Andes region tends to follow a systematic process of transitions, where pastures, croplands, and secondary vegetation are systematically replaced by each other. The same process was observed by Wassenaar *et al*. (2007) for Central America and the tropical part of South America. In the Colombian Andes, this trend is related to the presence of small properties traditionally dedicated to agricultural activities but integrating short periods of rest. Transitions are generally observed in areas with high economic activity and population density (highlands and East Mountain Range).

### *Submodels and drivers of change*

Our study demonstrates the importance of the attractors of change in all submodels, except distance to roads for the submodels of lowland forest deforestation and conversion to pasture. Freitas, Hawbaker, and Metzger (2010) indicate that although this variable is a strong predictor of forest dynamics in deforestation processes, its effect is detected only when agricultural expansion has stabilized over a certain period of time, as this is the case with montane forests that present the greatest Cramer value for this attractor. Distance to pastures is especially important regarding transitions in the region, suggesting that it stimulates the processes of land use and change and it should be considered in future studies as a dynamic variable.

The results of the deforestation submodels propose a spatial distribution of deforestation in montane forests associated with intensive agriculture. In this case, industries like coffee and cattle farming have economic stability because of the presence of roads and the proximity to intermediate and large population zones. Deforestation in lowland forests depends on the biophysical conditions of the area, particularly fertility, land type, and rainfall, and it is characteristic of marginal areas with itinerant farmers. This fact is consistent with the study by Rudel and Roper (1997) and the observations by Koning, Veldkamp, and Fresco (1998) in the Ecuadorian Andes. Although many of the social and economic variables were not significant in the deforestation submodels, Armenteras *et al*. (2011) note that some of these variables may affect the rates of deforestation in the Colombian Andes. The areas surrounding montane forests had exhibited economic consolidation in the past, leaving only forest remnants associated with protected or inaccessible areas, which is a process similar to the classical deforestation pattern found in mountain areas (Brandt and Townsend 2006). Armenteras *et al*. (2011) also argue that lowland forest areas in the region have reached different stages of colonization, with growing rural populations, pastures expansion, crops establishment, and large land availability. In these areas, the illegal coca cultivation increases the probability of forest conversion in the region (Dávalos *et al*. 2011), and generally this variable is related to forced population migration and unsatisfied basic needs.

The pasture conversion submodel is explained by few variables related to abiotic factors. Although a small reduction in pasture area was observed in this region during the period 1985–2000, the number of pastures are expected to increase in Latin America (Brandt and Townsend 2006; Wassenaar *et al*. 2007), and particularly in Colombia (Etter *et al*. 2006; Orrego 2009). Our results are consistent with those of Orrego (2009), who undertook a study in a subregion of the Colombian Andes and explained that the decline in pastures over a time period similar to ours was due to a transitory decrease in net incomes from livestock.

Population displacement has a particular importance for the submodels of abandonment and deforestation in lowland forests. Kaimowitz and Faune (2003) also indicate that violence has affected population migration, favoring the increase of secondary forests and abandoned lands. Cramer, Hobbs, and Standish (2008) state that the causes of abandoned lands are a complex mixture between social, economical, and ecological factors and that the increase of rural–urban migration is currently a worldwide tendency. In the Colombian Andes, many recovered areas are not influenced by incentives for conservation or the adoption of friendly agriculture techniques for the benefit of biodiversity or market trends, as has occurred in some Central American countries (Lugo 2002; Redo *et al*. 2009). Instead these areas respond to socioeconomic events that have occurred in Colombia over the past 20 years.

### *Scenarios and conservation impacts*

According to our results, the pasture conversion scenario shows a considerably different percentage of forest loss compared with the other two scenarios (almost three times more than RES for 2020), and it is the only scenario in which an increase in secondary vegetation associated with the Andes–Pacific transition zones is expected. This reduction in forests could have a large impact on the structural and functional connectivity of the region affecting the Andean ecosystem services considered important in terms of biodiversity, water, and climate regulation. At the same time, in this scenario the secondary vegetation increases strongly. This increase probably is related to the abandon of cattle and agricultural lands (abandonment submodel) or to the recovery of forests. The IPS shows two contradictory tendencies: the loss of forests and paramos but also the potential increase of secondary vegetation.

The CIS gave intermediate results between RES and IPS for forests and paramos. It is interesting to note that the results of the CIS for agriculture follow the current tendencies of the region (1985–2000), and the absence of tendencies toward an impact for the forests is not clear. In the Andean region, the agriculture at a great scale is already established (coffee, rice, and sugar zones) and future agricultural projects will be developed in transformed landscapes or at the borders with other regions of Colombia.

The three scenarios identify very similar areas that will undergo spatial change. Paramos, the Andean forests of the East Mountain Range, and the lowland forest of Amazonia and Orinoco are the most vulnerable areas to spatial changes through time. The economic development projected for the country in agro-industrial and petroleum sectors agrees with the zones where changes of future scenarios are more evident (Figure 5). In these areas, the social and economic dynamics are complex and a further agricultural expansion could have repercussions in the loss of corridors of connection between Andean ecosystems and tropical rainforest ecosystems. The landscapes will be more fragmented than the current ones, and the ecological processes related to the maintenance of the function of the ecosystems (regulation, migration, and displacement of plants and animals) probably could be interrupted.

The loss of lowland forests will likely occur in buffer areas surrounding several national parks in the Andes–Amazon transition region (Picachos and Alto Fragua, the Eastern Mountain Range) and parts of the Pacific slope (Figure 5). However, the protected areas could be an effective strategy to avoid deforestation and reduce other drivers of change; under this situation the protected areas can be considered as core areas for the connectivity in the region. The loss of paramos will likely lead to declining water resources that affect the water supply for large cities such as Bogotá, where most of the urban population of Colombia is concentrated (Galvis 2001). The transition of paramos to pastures and crops such as potatoes will increase the risk of fires and habitat degradation, affecting endemic species and increasing the vulnerability of these high mountain ecosystems (Pauli, Gottfried, Hohenwallner, Reiter, and Grabherr 2005).

The capacity of the Andean ecosystems to adapt to changes under the proposed scenarios, together with the effects of the climate change, can cause potential impacts over hydrological, ecological, and social systems in mountain regions in the area (Beniston 2003; IPCC 2007c; Rodríguez, Pabón Bernal and Martinez 2010). Social and political decisions will have a decisive role in determining the most appropriate schemes and strategies of land use where a balance is desired between conservation and development. Although trends of forest and paramos loss will continue in the future, current policy actions such as restricting mining projects in these areas or the adoption of REDD projects will be reflected in the medium term.

## Conclusions

Our research shows that about 33% of the study area experienced a transition from one category to a different category during the 15-year accounting period and about 25% is attributable to swap change. The categories of cropland, pasture, and secondary vegetation present systematic transitions as a traditional practice of land use in the region. The transition trends of LUCC in the Andes vary spatially in the region, and they are mainly related to attractors of change and biophysical characteristics. LUCC dynamics studies in the Andes should always consider the high intraregional variability in the region, including multiple factors and sociopolitical context in order to implement management strategies directly tackling the LUCC transitions likely to occur in a specific area. These results show that certain areas are likely to experience pressure, and in these areas the land use planning must be a goal for the decision makers taking into consideration all conservation of biodiversity, land management, protected areas management, and development models across different sectors.

The adoption of appropriate strategies in land use must consider the dynamics of LUCC and the interactions between ecological, social, and economic system of the region.

Concepts such as planning sustainable landscape associated with ecological network may be an appropriate way to work, which aims to identify important areas for the maintenance of ecosystem services in agricultural or livestock matrix. Some areas that currently represent remnant corridors of connection between lowland and montane ecosystems may experiment land use change in a future associated with deforestation. In these areas, we suggest strong political actions including the declaration or expansion of buffer areas around protected areas or incentives that reduce the pressures for change, such as REDD schemes.

Finally, further studies of LUCC in the region should focus on identifying intra-regional differences to capture the complexity of land use change, the systematical transition processes, and the assessment of intensity of land use that are relevant for the landscape planning. In the same way, to understand the abandonment submodel and the secondary vegetation dynamic is a challenge of investigation, which will permit to evaluate the ecological importance of these components related to the conservation and the ecosystem services maintenance.



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## References

Achard, F., Eva, H., Stibig, H.J., Mayaux, P., Gallego, J., Richards, T., and Malingreau, J.P. (2002), "Determination of Deforestation Rates of the World's Humid Tropical Forests," *Science*, 297, 999–1002.

Alo, C., and Pontius, Jr., R.G. (2008), "Identifying Systematic Land Cover Transitions Using Remote Sensing and GIS: The Fate of Forests Inside and Outside Protected Areas of Southwestern Ghana," *Environment and Planning B*, 35, 280–295.

Armenteras, D., Rodríguez, N., Retana, J., and Morales, M. (2011), "Understanding Deforestation in Montane and Lowland Forests of the Colombian Andes," *Regional Environmental Change*, 11, 693–705.

Asner, G.P., Rudel, T.K., Rudel, A.M., DeFries, R., and Emerson, R. (2009), "A Contemporary Assessment of Change in Humid Tropical Forests," *Conservation Biology*, 23, 1386–1395.

Beniston, M. (2003), "Climatic Change in Mountain Regions: A Review of Possible Impacts," *Climatic Change*, 59, 5–31.

Bouwman, A.F., Van Der Hoek, K.W., and Van Drecht, G. (2006), "Modelling Livestock-Crop-Land Use Interactions in Global Agricultural Production Systems," in *Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4*., eds. A.F. Bouwman, T. Kram and K.K. Goldewijk. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency (MNP).

Brandt, J.S., and Townsend, P.A. (2006), "Land Use – Land Cover Conversion, Regeneration and Degradation in the High Elevation Bolivian Andes," *Landscape Ecology*, 21, 607–623.

Brovkin, V., Claussen, M., Driesschaert, E., Fichefet, T., Kicklighter, D., Loutre, M.F., Matthews, H.D., Ramankutty, N., Schaeffer, M., and Sokolov, A. (2006), "Biogeophysical Effects of Historical Land Cover Changes Simulated by Six Earth System Models of Intermediate Complexity," *Climate Dynamics*, 26, 587–600.

Bush, M.B., Silman, M.R., and Urrego, D.H. (2004), "48,000 Years of Climate and Forest Change in a Biodiversity Hot Spot," *Science*, 303, 827–829.

CDB. Secretaría del Convenio sobre la Diversidad Biológica. (2010), *Perspectiva Mundial sobre la Diversidad Biológica 3*. Montreal.

CIAT – International Center of Tropical Agriculture. (2000), *Base de datos climatológicos*, Palmira, Colombia: author.
CODHES – Consultoría para los derechos humanos y el desplazamiento. (2005), *Monitoreo de población desplazada 1999–2005.* http://www.codhes.org.
Cramer, V.A., Hobbs, R.J., and Standish, R.J. (2008), "What's New About Old Fields? Land Abandonment and Ecosystem Assembly. Review," *Trends in Ecology & Evolution*, 23, 104–112.
DANE – National Administrative Department of Statistics. (1985–2005), *National Census of population for 1985 and 2005.* Bogotá, Colombia: author.
Dávalos, L.M., Bejarano, A.C., Hall, M.A., Correa, H.L., Corthals, A.P., and Espejo, O.J. (2011), "Forests and Drugs: Coca-Driven Deforestation in Global Biodiversity Hotspots," *Environmental Science and Technology*, 45, 1219–1227.
DNP – National Planning Department. (2005), *Indicadores económicos*, Bogotá, Colombia: author.
Duraiappah, A., Naeem, S., Agardi, T., Ash, N., Cooper, D., Díaz, S., et al. (eds.) (2005), *Ecosystems and Human Well-Being: Biodiversity Synthesis*, Washington, DC: Island Press.
Eastman, R. (2007), *Land Change Modeler Tutorial*, Worcester MA: Clark University.
Etter, A., McAlpine, C., and Possingham, H. (2008), "Historical Patterns and Drivers of Landscape Change in Colombia Since 1500: A Regionalized Spatial Approach," *Annals of the Association of American Geographers*, 98, 2–23.
Etter, A., McAlpine, C., Wilson, L., Phinn, S., and Possingham, H. (2006), "Regional Patterns of Agricultural Land Use and Deforestation in Colombia," *Agriculture, Ecosystems and Environment*, 114, 369–386.
Etter, A., and Van Wyngaarden, W. (2000), "Patterns of Landscape Transformation in Colombia, with Emphasis in the Andean Region," *Ambio*, 29, 432–439.
Feres, J.C., and Mancero, X. (2001), El Método de las Necesidades Básicas Insatisfechas (NBI) y sus Aplicaciones en América Latina. Santiago, Chile: Naciones Unidas - CEPAL.
Flamenco-Sandoval, A., Martínez-Ramos, M., and Masera, O.R. (2007), "Assessing Implications of Land-Use and Land-Cover Change Dynamics for Conservation of a Highly Diverse Tropical Rain Forest," *Biological Conservation*, 138, 131–145.
Foley, J.A., Heil Costa, M., Delire, C., Ramankutty, N., and Snyder, P. (2003), "Green Surprise? How Terrestrial Ecosystems Could Affect Earth's Climate," *Frontiers in Ecology and Environment*, 1, 38–44.
Freitas, S.R., Hawbaker, T.J., and Metzger, J.P. (2010), "Effects of Roads, Topography, and Land Use on Forest Cover Dynamics in the Brazilian Atlantic Forest," *Forest Ecology and Management*, 259, 410–417.
Galvis, L.A. (2001), *La topografía económica de Colombia*. Cartagena, Colombia: Banco de La República.
Gómez-Mendoza, L., Vega-Pena, E., Ramírez, M., Palacio-Prieto, J.L., and Galicia, L. (2006), "Projecting Land-Use Change Processes in the Sierra Norte of Oaxaca, Mexico," *Applied Geography*, 26, 276–290.
Hansen, A.J., Neilson, R.P., Dale, V.H., Flather, C.H., Iverson, L.R., Currie, D.J., Shafer, S., Cook, R., and Bartlein, P.J. (2001), "Global Change in Forests: Responses of Species, Communities, and Biomes," *Bioscience*, 51, 765–779.
Heistermann, M., Muller, C., and Ronneberger, K. (2006), "Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land-Use Modeling," *Agriculture, Ecosystems and Environment*, 114, 141–158.
IMAGE-team. (2001), *The IMAGE 2.2 Implementation of the SRES Scenarios. A Comprehensive Analysis of Emissions, Climate Change and Impacts in the 21st Century*, Bilthoven, The Netherlands: National Institute for Public Health and the Environment.
IGAC – Instituto Geográlfico Agustín Codazzi and Corpoica. (2002), *Mapa de Zonificación de los conflictos de uso de las tierras en Colombia. Escala 1:500.000*, Bogotá, Colombia: author.
IGAC – Instituto Geográfico Agustín Codazzi. (2005), *Oficial cartography, Escala 1:500.000*, Bogotá, Colombia: author.
IGAC – Instituto Geográfico Agustín Codazzi. (2008), *Mapa De Cobertura De La Tierra De Colombia, Escala 1:100000*, Bogotá, Colombia: author.
IPCC. (2000), "Afforestation, Reforestation, and Deforestation (ARD) Activities," in *Land Use, Land-Use Change and Forestry*, eds. R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, and D.J. Dokken, Cambridge, UK: Cambridge University Press.

IPCC. (2007a), "Ecosystems, Their Properties, Goods and Services," in *Climate Change 2007. Impacts, Adaptation and Vulnerability*, eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, Cambridge, UK: Cambridge University Press.

IPCC. (2007b), "Latin America in Climate Change 2007: Impacts, Adaptation and Vulnerability," in *Climate Change 2007. Impacts, Adaptation and Vulnerability*, eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, Cambridge, UK: Cambridge University Press.

IPCC. (2007c), in *Climate Change 2007: Mitigation of Climate Change*, eds. B. Metz, O. Davidson, P.R. Bosch, R. Dave and L.A. Meyer, Cambridge, UK : Cambridge University Press.

Kaimowitz, D., and Fauné, A. (2003) "Contras and Comandantes: Armed Movements and Forest Conservation in Nicaragua's Bosawas Biosphere Reserve," in *War and Tropical Forests: Conservation in Areas of Armed Conflict*, ed. S. Price, New York: Haworth Press.

Keese, J., Mastin, T., and Yun, D. (2007), "Identifying and Assessing Tropical Montane Forests on the Eastern Flank of the Ecuadorian Andes," *Journal of Latin American Geography*, 6, 63–94.

Kintz, D.B., Young, K.R., and Crews-Meyer, K.A. (2006), "Implications of Land Use/Land Cover Change in the Buffer Zone of a National Park in the Tropical Andes," *Environmental Management*, 38, 238–252.

Koning, G.H.J., Veldkamp, A., and Fresco, L.O. (1998), "Land Use in Ecuador: A Statistical Analysis at Different Aggregation Levels," *Agriculture, Ecosystems and Environment*, 70, 231–247.

Lambin, E.F., and Geist, H. (2006) *Land-Use and Land-Cover Change: Local Processes and Global Impacts*, The IGBP Series, Berlin: Springer.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O., Dirzo, R., Fischer, G., Folke, C., George, P.S., Homewood, K., Imbernon, J., Leemans, R., Li, X., Moran, E.F., Mortimore, M., Ramakrishnan, P.S., Richards, J.F., Skånes, H., Steffen, W., Stone, G., Svedin, U., Veldkamp, T.A., and Vogel, C. (2001), "The Causes of Land-Use and Land-Cover Change: Moving Beyond the Myths," *Global Environmental Change*, 11, 261–269.

Lugo, A.E. (2002), "Can We Manage Tropical Landscapes? – An Answer from the Caribbean Perspective," *Landscape Ecology*, 17, 601–615.

Mahecha, L., Gallego, L.A., and Peláez, F.J. (2002), "Situación Actual De La Ganadería De Carne En Colombia Y Alternativas Para Impulsar Su Competitividad Y Sostenibilidad," *Revista Colombiana de Ciencias Pecuarias*, 15, 213–225.

Manandhar, R., Inakwu, O.A., and Pontius, Jr., R.G. (2010), "Analysis of Twenty Years of Categorical Land Transitions in the Lower Hunter of New South Wales, Australia," *Agriculture, Ecosystems and Environment*, 135, 336–346.

Martínez, M.L., Pérez-Maqueo, O., Vázquez, G., Castillo-Campos, G., García-Franco, J., Mehltreter, K., Equihua, M., and Landgrave, R. (2009), "Effects of Land Use Change on Biodiversity and Ecosystem Services in Tropical Montane Cloud Forests of Mexico Forest," *Forest Ecology and Management*, 258, 1856–1863.

Mayaux, P., Holmgren, P., Achard, F., Eva, H., Stibig, H., and Branthomme, A. (2005), "Tropical Forest Cover Change in the 1990s and Options for Future Monitoring," *Philosophical Transactions of the Royal Society B*, 360, 373–384.

Meidinger, D.V. (2003), *Protocol for accuracy assessment of ecosystem maps*, Technical Report 011, Victoria BC: British Columbia Ministry of Forests Research Branch..

Mittermeier, R.A., Myers, N., and Mittermeier, C. (1999), *Biodiversidad amenazada: Las ecorregiones terrestres prioritarias del mundo*, México D.F.: Cemex, Conservation International y Agrupación Sierra Madre.

Myers, N. (1998), "Threatened Biotas: 'Hotspots' in Tropical Forests," *The Environmentalist*, 8, 1–20.

Orrego, S. (2009), "Economic Modeling of Tropical Deforestation in Antioquia (Colombia), 1980–2000: An Analysis at a Semi-Fine Scale with Spatially Explicit Data," unpublished Ph.D. dissertation, Oregon State University.

Pauli, H., Gottfried, M., Hohenwallner, D., Reiter, K., and Grabherr, G. (2005), "Ecological Climate Impact Research in High Mountain Environments: GLORIA (Global Observation Research Initiative in Alpine Environments) – Its Roots, Purpose and Long-Term Perspectives," *Global Change and Mountain Region*, 23, 383–391.

Pontius, Jr., R.G., Boersma, W., Castella, J.C., Clarke, K., de Nijs, T., Dietzel, C., Duan, Z., Fotsing, E., Goldstein, N., Kok, K., Koomen, E., Lippitt, C., McConnell, W., Sood, A., Pijanowski, B., Pithadia, S., Sweeney, S., Trung, T.N., Veldkamp, T., and Verburg, P.H. (2008), "Comparing the

Input, Output, and Validation Maps for Several Models of Land Change," *The Annals of Regional Science*, 42, 11–47.
Pontius, Jr., R.G., and Millones, M. (2011), "Death to Kappa: Birth of Quantity Disagreement and Allocation Disagreement for Accuracy Assessment," *International Journal of Remote Sensing*, 32, 4407–4429.
Pontius, Jr., R.G., Peethambaram, S., and Castella, J.C. (2011), "Comparison of Three Maps at Multiple Resolutions: A Case Study of Land Change Simulation in Cho Don District, Vietnam," *Annals of the Association of American Geographers*, 101, 45–62.
Pontius, Jr., R.G., Shusas, E., and McEachern, M. (2004), "Detecting Important Categorical Land Changes While Accounting for Persistence," *Agriculture, Ecosystems & Environment*, 101, 251–268.
Puyravaud, J.P. (2003), "Standardizing the Calculation of the Annual Rate of Deforestation," *Forest Ecology and Management*, 177, 593–596.
Redo, D., Joby Bass, J.O., and Millington, A.C. (2009), "Forest Dynamics and the Importance of Place in Western Honduras," *Applied Geography*, 29, 91–110.
RESNATUR – Asociación Red Colombiana de Reservas Naturales de la Sociedad Civil. (2000), *Mapa de reservas naturales de la Sociedad Civil*, Bogotá, Colombia: author.
Rodríguez, N., Armenteras, D., Morales, M., and Romero, M. (2006), *Ecosistemas De Los Andes Colombianos*, Bogotá, Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt.
Rodríguez, N., Pabón, J.D., Bernal, N.R., and Martínez, J. (2010), *Cambio Climático Y Su Relación Con El Uso Del Suelo En Los Andes Colombianos*, Bogotá, Colombia: Instituto de Investigación de Recursos Biológicos Alexander von Humboldt..
Rudel, T., and Roper, J. (1997), "The Paths to Rain Forest Destruction: Crossnational Patterns of Tropical Deforestation, 1975–90," *World Development*, 25, 53–65.
Rudel, T.K., Bates, D., and Machinguiashi, R. (2002), "A Tropical Forest Transition? Agricultural Change, Out-Migration, and Secondary Forests in the Ecuadorian Amazon," *Annals of the Association of American Geographers*, 92, 87–102.
Rudel, T.K., DeFries, R., Asner, G.P., and Laurence, W. (2009), "Changing Drivers of Deforestation and New Opportunities for Conservation," *Conservation Biology*, 23, 1396–1405.
Sala, O.E., Chapin, I.F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.H., Mooney, H.A., Oesterheld, M., Leroy Poff, N., Sykes, M.T., Walker, B.H., Walker, M., and Wall, D.H. (2000), "Global Biodiversity Scenarios for the Year 2100," *Science*, 287, 1770–1774.
Sala, O.E., van Vuuren, D., Pereira, H., Lodge, D., Alder, J., Cumming, G.S., Dobson, A., Wolters, V., and Xenopoulos, M. (2005), "Biodiversity Across Scenarios," in *Ecosystems and Human Well-Being: Scenarios*, eds. S.R. Carpenter, P.L. Pingali, E.M. Bennett, and M. Zurek, Washington, DC: Island Press.
Sarmiento, R. (2000), "Breaking Mountain Paradigms: Ecological Effects on Human Impacts in Mane-Aged Tropandean Landscapes," *Ambio*, 29, 423–431.
SUI – Sistema Único de Información de Servicios Públicos. (2005), *Informes integrales de servicios públicos*, Bogotá, Colombia: author.
UNEP – United Nations Environment Programme (2007), *Global Environment Outlook GEO 4: Environment for Development*, Valleta, Malta: UNEP.
UNEP – United Nations Environment Programme (2010), *Latin America and the Caribbean: Environment Outlook, GEO LAC 3*, Panamá: UNEP.
UPME – Unidad de Planeación Minero Energética. (2005), *Mapa de concesiones mineras*, Bogotá, Colombia: author.
Van Ausdal, S. (2009), "Pasture, Profit, and Power: An Environmental History of Cattle Ranching in Colombia, 1850–1950," *Geoforum*, 40, 707–719.
Van der Hammen, T. (1992), *Historia, Ecología Y Vegetación*, Bogotá, Colombia: Corporación Araracuara.
Veldkamp, A., and Lambin, E.F. (2001), "Predicting Land Use Change," *Agriculture, Ecosystems and Environment*, 85, 1–6.
Wassenaar, T., Gerber, P., Verburg, P.H., Rosales, M., Ibrahim, M., and Steinfeld, H. (2007), "Projecting Land Use Changes in the Neotropics: The Geography of Pasture Expansion," *Global Environmental Change*, 17, 86–104.