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Environmental predictors of forest change: An analysis of natural predisposition to deforestation in the tropical Andes region, Peru

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ABSTRACT

The spatial patterns of deforestation are usually non-randomly distributed across the landscape. While anthropogenically driven processes are often addressed in land-use regulation policies and deforestation research, less attention is given to the environmental factors that influence tropical deforestation. This study investigates to what extent climate conditions (temperature and precipitation) and biophysical landscape characteristics (elevation, slope, soil type, forest type, and distance to rivers) facilitate or mitigate deforestation processes in Peru's tropical Andes. A Random Forest regression model was constructed for the entire Peruvian tropical Andes, and separate models were developed for some of the known direct deforestation drivers in the region (coca production, gold mining, and land-use by indigenous and non-indigenous communities). Soil type and precipitation were identified as the most important deforestation predictors when the entire Peruvian tropical Andes was considered, whereas distance to rivers was associated with deforestation by mining activities, and elevation and temperature with coca cultivation areas. Using the regression results, a Random Forest classification model was constructed to locate areas where the composition of environmental factors could either facilitate or mitigate deforestation processes. It was found that almost 85% of the forests classified as having high to very high probability to deforestation were located outside current protected areas. In order to increase conservation impacts, the results suggest that greater consideration should be given to the distribution of environmental factors when designing land-use regulation policies and establishing protected areas.

1. Introduction

Ongoing processes of forest destruction across tropical regions pose a major threat to biodiversity, climate stability and the functioning of biogeochemical and hydrological cycles (Bonan, 2008; Malhi et al., 2008). In spite of the worldwide recognition of this environmental problem and the implementation of manifold initiatives to halt further reduction of tropical forest areas, the rates of deforestation in the tropics have remained consistently at high levels (Achard et al., 2014; Sloan & Sayer, 2015). Much attention goes to the tropical forest ecosystems in Central and South America, which harbor some of the world's greatest amounts of species diversity (Poveda, Álvarez, & Rueda, 2011; Ribeiro et al., 2011, pp. 405–434) and constitute the largest portion of the global terrestrial carbon sink (Pan et al., 2011). Between 2000 and 2010, the extent of forest cover in Central and South America shrunk by approximately 55,000 km^2 per year, with important deforestation hotspots located in northern Argentina, southeastern Bolivia, western Paraguay and the Brazilian Amazon (Aide et al., 2013). According to recent land-use change scenarios for the Neotropics (Soares-Filho et al., 2013), in particular the lowland Amazon basin and forests located at the Andean foothills will experience extensive forest losses in the future, whereas forest recovery could be expected in the highland forests of the Andean mountain range (Middendorp, Pérez, Molina, & Lambin, 2016; Sanchez-Cuervo & Aide, 2013a). These dynamics of Neotropical forest cover change will largely shape the future well-being of people relying directly on forest ecosystem services.

In the last decades, substantial efforts have been made by researchers to determine why forest change happens and why the patterns and rates of forest change vary across the landscape (Rudel, 2007). An important contribution to the deforestation literature is the work by Geist and Lambin (2002), which conceptualizes the dynamics between fundamental social processes such as population changes, and human activities or actions at the local level with direct impacts on forest cover such as logging and agricultural expansion. Proximate causes and underlying driving forces typically relate to anthropogenic systems, however, environmental factors are also recognized to play a crucial role in the process of forest cover change. Geist and Lambin (2002) reviewed 152 subnational case studies from the tropical belt, out of

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which a third reported a link between deforestation and factors associated with the biophysical environment, including a range of landscape attributes and climate variables. The effect of these environmental factors is linked to human behavior at the local level, as they set the necessary conditions for land-use change processes to occur, and place physical thresholds on the types of land-use practices that are feasible in a region (Aide et al., 2013). While this emphasizes the importance of considering landscape elements and climate conditions at local scales, the mainstream deforestation literature is particularly oriented towards analyzing the political, economic, and social context in which forest change processes occur (Jusys, 2016; Lambin et al., 2001; Robinson, Holland, & Naughton-Treves, 2014; Rudel, Defries, Asner, & Laurance, 2009).

Nonetheless, a great variety of models have been developed throughout the years to describe the role of the natural environment in the deforestation process (Busch & Ferretti-Gallon, 2017; Kaimowitz & Angelsen, 1998). The environmental variables commonly included in models relate to land accessibility, land suitability and climate variability. Landscape characteristics that provide natural access routes to forests include rivers and lakes (Salonen, Toivonen, Cohalan, & Coomes, 2012), especially in areas where roads and other infrastructure is scarce (Armenteras, Rudas, Rodriguez, Sua, & Romero, 2006). Furthermore, forests located along the coastline that were better accessible were found to be subjected to more deforestation compared to mainland forests (Rudel & Roper, 1996). Elevation and slope gradients have been associated with forest accessibility and deforestation as well (Bax, Francesconi, & Quintero, 2016), although they particularly determine the suitability of the land for productive activities (Pope et al., 2015). Higher sloped terrain is less attractive for agriculture, given that harvests are generally lower (Barrowclough et al., 2016) and working the land requires greater efforts and resources (Grau, Kuemmerle, & Macchi, 2013). The relationship between deforestation and topography is likely to become weaker through time when low-lying lands become scarcer and exhausted, leaving people no other choice but to move to steeper areas. Deforestation induced by the suitability of the land is also determined by the quality of the soil, mainly within the context of agricultural production (Laurance et al., 2002), and by forest type (Chowdhury, 2006), given the potential preferences of loggers for tree species with high economic value (Asner et al., 2005). Climate also seems to affect deforestation through local variations in precipitation, temperature, and dry season severity. Precipitation and dry season severity can either have a hindering or an enabling effect: less rainfall results in dryer forests which are easier to burn (Aragao et al., 2008) while deficit or excessive rainfall tends to reduce crop yields (Grau, Gasparri, & Aide, 2005). On the other hand, areas characterized by moderate local temperatures provide desirable conditions for establishing human settlements, which transform the natural landscape (Armenteras, Rodríguez, Retana, & Morales, 2011).

Given that the tropical Andes region is characterized by a great variation in altitude, forest structure, temperature and rainfall patterns, the way in which land cover transformations are being undertaken could be related to these environmental attributes. A better understanding of nature's influence on deforestation decision making (here defined as the decision of land-managers to conserve or convert forest) is needed, as it is currently not adequately addressed in land-use regulation policies (Joppa & Pfaff, 2009; Miteva, Pattanayak, & Ferraro, 2012). However, studies specifically focusing on the environmental dimensions of deforestation are scarce. Generally more attention is given to human-related drivers and causes. To the best of our knowledge, the work by Rolett and Diamond (2004) may be the best known study that focuses on the effect of predisposing environmental factors on forest transitions. Hence, understanding the biophysical and climate context of forest cover change in the highly diverse landscape of the Andean mountains could advance our understanding of montane forest management. Furthermore, most studies on deforestation in the Neotropical region focus on lowland Amazon ecosystems, while information on Andean ecosystems remains limited (Armenteras et al., 2011; Zuluaga & Rodewald, 2015). In particular, very few studies have analyzed deforestation practices in the Peruvian Andes region. Current rates of forest cover change and hotspot locations in the Peruvian Andes are not provided in the scientific literature, and the drivers associated with these changes are not clearly understood (Robiglio, Armas, Silva Aguad, & White, 2014). Nonetheless, the tropical Andes have been identified as the most critical biodiversity hotspot on the planet in terms of plant and vertebrate species richness (Myers, Mittermeier, Mittermeier, Da Fonseca, & Kent, 2000), which emphasizes the importance of investigating deforestation dynamics in this region. More specifically, the objectives of this study were to 1) identify and examine the environmental factors that facilitate or mitigate deforestation in the tropical Peruvian Andes; 2) analyze the influence of these environmental factors on some of the known direct deforestation drivers in the region; and 3) map the areas where the natural landscape facilitates or mitigates deforestation.

2. Methods

2.1. Study area

Peru's tropical forest region can be disaggregated into the lowland Amazon consisting of humid forests at low elevations, the northern coast region consisting of dry forests, and the tropical Andes region consisting of sub-tropical forests located along the eastern slopes and valleys of the Andean mountain range. The Peruvian tropical Andes are located between coordinates 3°5′10 South, 79°1′15 West, 14°29′24 South and 68°49′37 West, with most of the forests located at elevations ranging from 500 up to 3000 m.a.s.l. (MINAM, 2015). The tropical Andes extend over approximately 190,000 km^2, which represents about 15% of the national territory (Fig. 1). Rainfall varies considerably, from 300 mm to 6000 mm per year, with the wettest areas found in the south and the center at elevations between 500 and 800 m.a.s.l. Peru's Ministry of the Environment distinguishes twenty-three different types of mature forest within the elevation range of 500–3000 m.a.s.l., including tropical floodplain forests, high terraces, palm tree forests and cloud forests (MINAM, 2015). Other natural ecosystems include Andean savanna vegetation and grasslands mainly located at higher elevations. Soils with good biophysical properties for agricultural production, including eutric and dystric cambisols (FAO-Unesco, 1990, p. 60) are found at lower elevations along the eastern edge of the tropical Andes and in central regions of the San Martín and Junín departments.

Peru currently comprises a total of 40 national parks, communal reserves, national monuments and protected forests, out of which 22 are partly or completely located within the tropical Andes, covering about 25% of the area. Road density in the region is relatively low (8 km per 100 km^2) owing to the highly sloped and arboreal landscape. In consequence, the region is sparsely populated: an estimated 1.2 million people (INEI, 2015) are scattered over hundreds of small settlements and a few bigger urban centers such as the cities of Rioja and Moyobamba in the San Martín department, and the city of Tingo María located in Huánuco. The rural population can be subdivided in indigenous inhabitants who originate from the region, and non-indigenous or colonist communities from varying regions of Peru. Rural livelihoods are largely based on small scale and commercial agriculture, as well as livestock farming activities. Some of the principal crops include coffee, which is produced at elevations ranging from 700 to 1200 m.a.s.l. primarily in the departments of Junín, Cusco, and San Martín (Tulet, 2010); while rice and cassava are primarily cultivated in San Martín, Loreto and Amazonas (INEI, 2014), and maize in San Martín, Huánuco, Loreto and Junín (INEI, 2014). The tropical Andes are marked by a long history of widespread cultivation of illicit coca leaves, with massive impacts on forests and other biological diversity. The production of cocaine has been accountable for large scale ecosystem degradation in the Cusco region in the 1960s (Dourojeanni, 1992) and