Applied Geography 75 (2016) 188–199

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

# Fundamental causes and spatial heterogeneity of deforestation in Legal Amazon

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A R T I C L E I N F O

*Article history:*
Received 27 December 2015
Received in revised form
12 August 2016
Accepted 23 August 2016
Available online 9 September 2016

*Keywords:*
Deforestation
Amazon
Google
Spatial heterogeneity
GWR

A B S T R A C T

This study explores the main direct and underlying causes of deforestation in Brazil's Legal Amazon region by considering spatial differences. The computation of localized parameters is based on geographically weighted regression (GWR). The novelty of this paper lies in its incorporation of economic, rather than Euclidean, distances into the GWR. Economic distances are measured by travel time, sourced from Google Inc. A global approach revealed several important factors that affect deforestation, including: rural population, GDP (suggesting a U-shaped environmental Kuznets curve), forest stock, cattle ranching, timber value, and road networks (both official and unofficial). Local analysis uncovered patterns not seen under global models, especially in the state of Pará. Most notably, crop cultivation was found to accelerate deforestation in southeastern Pará and northeastern Mato Grosso, while in some regions (especially in the northeastern corner of Pará), the area covered by crop plantations was negatively associated with deforestation. For Pará, rural credit constraints, larger territories designated as sustainable use areas and indigenous lands, and higher levels of precipitation inhibit deforestation. Further, rural population has a very heterogeneous impact on deforestation across Legal Amazon: it is not a significant factor of deforestation in northern Pará and Amapá, but it has a relatively strong effect in the western parts of Mato Grosso and Rondônia. Also, official and illegal roads create significantly more pressure on forests in remote regions compared to developed areas. Finally, the use of economic distances, as opposed to Euclidean distances, leads to notably different GWR results.



## 1. Introduction

Reducing emissions from deforestation, a major source of $CO_2$, could be a highly cost-effective option for climate policy (Rametsteiner, Obersteiner, Kindermann, & Sohngen, 2009). Tropical deforestation also has other negative externalities, such as the loss of biodiversity, erosion, floods, and lowered water levels (Espindola, De Aguiar, Pebesma, Câmara, & Fonseca, 2011). As such, research into causes of deforestation has a long history. Some studies investigate a specific cause of deforestation. For instance, Arima, Richards, Walker, and Caldas (2011), Barona, Ramankutty, Hyman, and Coomes (2010), Macedo et al. (2012), and Morton et al. (2006) study the effect of agriculture on deforestation; Barber, Cochrane, Souza, and Laurance (2014) and Pfaff et al. (2007) investigate links between road networks and deforestation, and Carr and Burgdorfer (2013) discuss the implications of rural populations on forest clearing. Araujo, Araujo Bonjean, Combes, Combes, and Reis (2010), Bhattarai and Hamming (2001), Culas (2012), and Ehrhardt-Martinez, Crenshaw, and Jenkins (2002) test for an environmental Kuznets curve. Assunção, Gandour, Rocha, and Rocha (2013a) focus on causality between rural credit concessions and deforestation. Soares-Filho et al. (2006) assess the impact of protected areas. Araujo et al. (2010) investigate the effects of land insecurity on forests. Faria and Almeida (2016) explore the relation between openness to trade and deforestation. Other studies investigate the general causes of deforestation, including Aguiar, Câmara, and Escada (2007), Hargrave and Kis-Katos (2013), Laurance et al. (2002), and Reis and Guzman (1993). The most relevant empirical findings on the drivers of deforestation were surveyed by Angelsen and Kaimowitz (1999) and Geist and Lambin (2002).

Evidence from empirical case studies that identify both proximate causes and underlying forces at work on tropical deforestation suggests that no universal link between cause and effect exists (Geist & Lambin, 2002). This is because policy is made at village, county, state, and national levels, rather than consistently over an

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http://dx.doi.org/10.1016/j.apgeog.2016.08.015

area (Carr et al., 2012). The most popular technique to account for variability over such large land masses is called geographically weighted regression (GWR), developed by Brunsdon, Fotheringham, and Charlton (1998). Applications of GWR in deforestation and forest loss modeling can be found in Carr et al. (2012), Jaimes, Sendra, Delgado, and Plata (2010), Moon and Farmer (2012), Oliveira and Almeida (2011), and Witmer (2005). However, only Oliveira and Almeida (2011) applied GWR to the situation in Legal Amazon.

The objective of this study is to investigate the causes of deforestation in Legal Amazon, but with two important differences compared to Oliveira and Almeida (2011). Firstly, this study considers gross domestic product and demographic variables as endogenous, following recommendations by Angelsen and Kaimowitz (1999) and Kaimowitz and Angelsen (1998). Secondly, the weighting is based on economic, rather than geographical, distances, which are measured by travel time.

The extent of similarities between the results obtained by applying different distance measurement methods depends on the topographic characteristics of geographical regions, road networks, and an area's economic development, among other factors. If a territory is large, economically advanced, and has highly populated urban areas, straight lines are appropriate and represented by distances traveled by plane. However, in large, densely forested areas with numerous villages, plane connection is not cost-effective. Under such cases, ground transport is the only viable means of transportation. Here, the terrain itself is an important factor. For instance, in mountainous or densely forested areas, roads are winding (see Figure A.1), which leads to significant differences between road and straight line mileages. Moreover, considering only the mileage may be too restrictive, since roads are heterogeneous in quality and type. Undoubtedly, highways provide much faster access than dirt roads that cut through the landscape. Additionally, Legal Amazon has almost one hundred villages which can only be accessed via the river network, implying that access to these villages is slower than it would be in the presence of roads. Therefore, travel time is the most appropriate way to measure distances between locations in Legal Amazon.

## 2. Data and methods

The data covers 486 municipalities in Legal Amazon. Observations for which forest coverage was lower than 5% of the territory were omitted. Some municipalities were removed from the dataset because of a lack of information. Data available as shapefiles or in fine scale raster grids was aggregated to the level of municipalities in ArcGIS Version 10.0, ESRI, Redlands, CA, USA. Squares of GDP per capita were computed to test an environmental Kuznets curve. Past population and GDP per capita variables were used as instruments. This is a cross-sectional analysis, and the study year is 2010. Brief descriptions, units of measurements, and data sources are presented in Table 1. See appendix B for municipal level descriptive statistics. Furthermore, it was verified that no severe multicollinearity between the covariates exists (Table C.1). Nevertheless, the correlation coefficients reveal notable collinearity between rural credit per capita and GDP per capita, rural credit per capita and crop area, and official and unofficial roads.

As far as data regarding distance is concerned, the computation of straight line distances was based on decimal coordinates of municipality capitals, reported by the IBGE. Road and time distances used in the research are the property of Google Inc., located at 1600 Amphitheatre Parkway, Mountain View, CA 94043, United States. The distances are measured between municipality seats. The data was extracted using The Google Distance Matrix API service (Google Developers, 2014). However, almost one hundred locations in Legal Amazon do not offer road access. Therefore, distances by rivers between roadless municipality seats were computed in ArcGIS. The computations were based on a river shapefile, downloaded from

**Table 1**
Description of the variables.

| Abbreviation | Description | Unit | Source |
|---|---|---|---|
| DEF | Annual deforestation increments. Data on the municipal level is available on the INPE's website. It is aggregated from PRODES maps, which are distributed at a 60-m spatial resolution and are created by digital image processing and visual interpretation of LANDSAT ™ imagery on computer screens. | $km^2$ | INPE (2014) |
| POPURB | Number of urban inhabitants from 2010 census | count | IBGE (2014) |
| POPRUR | Number of rural inhabitants from 2010 census | count | IBGE (2014) |
| GDP | Gross domestic product per capita in 2010 | R$ (BRL) | IBGE (2014) |
| FCOVER | Extant forests | % | INPE (2014) |
| ELEV | Average elevation over 90 square meter cells that fall within the borders of a municipality | meter | SRTM (2014) |
| CATTLE | Cattle (bovines) | count | IBGE (2014) |
| CROP | Planted acreage of temporal (yearly) crops | ha | IBGE (2014) |
| TIMBER | Value of all timber products | R$ (BRL) | IBGE (2014) |
| ROF | Total length of official roads, excluding urban streets and roads under construction | km | GEOFABRIK. (2014) |
| RUNF | Total length of unofficial roads | km | IMAZON[a] |
| CREDIT | Sum of rural credit per capita, issued by official banks and credit cooperatives | R$ (BRL) | Central Bank of Brazil (2013) |
| TENURE | Percentage of private properties in total properties | % | IBGE (2014) |
| PREC | Annual precipitation over municipality seat (computed as in Arima et al., 2011). | mm | TRMM (2016) |
| STRICT | Territory designated as strict protection areas (IUCN categories I, II and III)[b] | % | WDPA (2015) |
| SUST | Territory designated as sustainable use areas (IUCN categories IV, V and VI) | % | WDPA (2015) |
| INDIG | Territory designated as indigenous lands | % | WDPA (2015) |
| TERR | Territory of a municipality | $km^2$ | IBGE (2014) |
| A | Autocovariate (normalized weighted sum of deforestation in the neighbors) | $km^2$ | Compiled by the author |
| POPURBLG | Number of urban inhabitants from 2000 census | count | IBGE (2014) |
| POPRURLG | Number of rural inhabitants from 2000 census | count | IBGE (2014) |
| GDPLG | Gross domestic product per capita in 2009 | R$ (BRL) | IBGE (2014) |

INPE: Brazil's National Institute of Space Research; SRTM: Shuttle Radar Topography Mission;
IBGE: Brazil's Institute of Geography and Statistics; IMAZON: Amazon's Institute of Human and Environment; TRMM: Tropical Rainfall Measuring Mission; WDPA: World Database on Protected Areas.
[a] See acknowledgements.
[b] For some records in the attribute table of the WDPA, a IUCN (International Union for Conservation of Nature) category of protected areas in the shapefile is not reported or is reported incorrectly. IUCN categories were taken from the cadastre of protected areas, managed by the Brazilian Ministry of Environment (MMA, 2016).