

Analyzing temporal and spatial dynamics of deforestation in the Amazon: a case study in the Calha Norte region, State of Pará, Brazil

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Abstract. In this study we analyzed the temporal and spatial dynamics of deforestation in the Amazon using spatial statistics. The analysis was carried out in the Calha Norte region, State of Pará, from 2000 to 2008, using deforestation data produced by the PRODES project. First, we used the Moran's I statistic to identify at which distance deforestation was spatially autocorrelated the most. Second, we performed the Hot spot analysis to identify clusters with high and low increments of deforestation. For this step we used the Getis-Ord G_i^* statistic. Until 2008 more than 94% of the deforestation occurred outside the protected areas at an annual rate of 151 km²/year (between 2000-2008). The increments of deforestation between 2000 and 2008 were spatially autocorrelated at a distance of 10 km, with a mean Moran's I value of 0.07 and a Z-score of 112.33. The Hot and Colds spots identified were concentrated in the Central-South region of the study area with two main regions identified as persistent Hot spots and persistent Cold spots. The methods used in this study have a strong potential to be replicated in others areas of the Brazilian Amazon.

Palavras-chave: moran's I, hot spot analysis, brazilian amazon, calha norte region.

1. Introduction

The Brazilian Amazon is experiencing the highest absolute rates of deforestation in the world (Ewers et al., 2008; Achard et al., 2002). More than 700,000 km² of forest have been deforested up until 2008, at an average annual rate of 18,759 km² between 2000 and 2008 (INPE, 2008). Deforestation leads to biodiversity loss (Vieira et al., 2008) and landscape fragmentation (Perez et al., 2008). It also contributes to global warming accounting for 20% of total carbon emissions across the planet (UN-REDD, 2009).

Deforestation in the Brazilian Amazon is influenced by two categories of potential drivers (Ewers et al., 2008). At a large scale, deforestation is influenced by factors not specific to the Brazilian Amazon region, such as Gross Domestic Product (GDP), inflation and exchange rates, credit availability, and the size of Brazil's international debt. At the local scale, deforestation is sensible to the size of protected areas, the size and price of cattle herds and soybean plantations, and the logging activity. Logging, agriculture, and cattle companies are motivated by economic factors to open (or recuperate) roads network, to facilitate access to forest, and to replace the forest areas by others land cover such as soybeans or cattle (Pfaff, 1999; Helmut and Lambin, 2001).

The process that encourages deforestation in the Amazon creates a spatial pattern associated with the presence of roads, topographic conditions, and market accessibility. For example, Brandão Jr. et al. (2007) found that 95% of the Amazon deforestation is concentrated in the first

5 km from roads. Analysis of the spatial patterns of phenomenon, such as deforestation, is important because it helps to better understand the geographic patterns, and the changes through time (Longley and Batty, 1997).

The spatial pattern of a geographic data can be identified in two ways: visually or using statistics. Visual identification is subjective and can lead to wrong information. On the other hand, the statistical approach compares the features' distribution to a hypothetical random distribution and helps to identify spatial patterns of the data (Mitchell, 2005). In order to understand temporal and spatial dynamics of deforestation in the Amazon region we used a statistical approach to answer two research questions. First, at what distance deforestation is spatially autocorrelated? Second, in which regions is deforestation clustered as a Hot spot (clusters of high annual rates of deforestation) or as a Cold spot (i.e. clusters of low annual rates of deforestation)?

2. Study Area

The study was carried out in the Calha Norte region located in the State of Pará, Brazil, between the coordinates 58.9W/51.9W and 2.6N/2.4S. This area covers more than 27 million ha and has a high potential to economic exploration by logging (Bandeira et al., 2010; Veríssimo et al., 2006) and mining (Silva, 2008) (**Figure 1**). More than 83% (22 million ha) of the area is protected by Brazilian Law, mostly for Indigenous Lands and Conservation Units. About 58% of the protected areas were created in December of 2006 by the State of Pará Government. The climate in this study area is tropical monsoon (Am) according to the Koppen climate classification, with elevation ranging from 50 meters to 1000 meters above sea level.

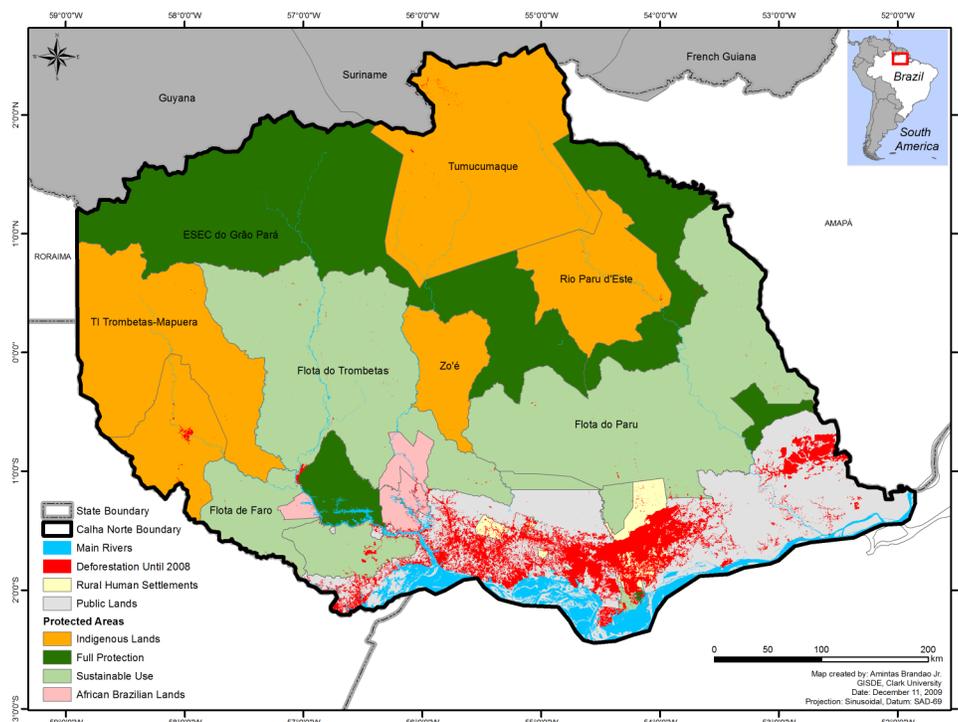


Figure 1. The Calha Norte region, State of Pará, Brazil.

3 Data and Methods

3.1 Data

The deforestation maps were produced by the Brazilian Institute of Space Research (INPE) through the PRODES project (INPE, 2008). Landsat and CBERS satellite images were used by INPE to identify deforestation (i.e. clear cut of the forest) that occurred up until 2000 and from 2000 to 2008. In addition, we used political boundaries (IBGE, 2007), boundaries of Conservation Units (IBAMA, 2008), Indigenous Lands (FUNAI, 2008) and Human Rural Settlements (INCRA, 2002). All data was organized in a Geographic Information System (GIS), using the Sinusoidal Projection, the SAD 1969 Datum, and ArcGIS 9.3.1 software.

3.2 Analyzing the spatial patterns and temporal dynamics of deforestation

We conducted four main steps to analyze the spatial patterns and temporal dynamics of deforestation. First we analyzed the geography of the deforestation. In the next step, we created a 1 km x 1 km grid and overlaid it with the increments of deforestation from 2000 to 2008. Next, we calculated the spatial autocorrelation of the deforested cells using the Moran's I method. Finally we used the Getis-Ord G_i^* statistic to perform the Hot/Cold spot analysis, assuming the distance with the highest spatial autocorrelation resulted from the previous step.

3.2.1 Calculating the spatial autocorrelation with Moran's I

The Moran's I measured the spatial autocorrelation (feature similarity) based on both feature location and feature values simultaneously (Mitchell, 2005; Moran, 1950). It evaluated whether the feature pattern was clustered, dispersed, or random. Moran's I values range from -1.0 to +1.0. A value near to +1.0 indicates clustering while an index value near -1.0 indicates dispersion. To determine if the Moran's I index was significant we evaluated the Z score and p-value. The hypothesis test in this case was that the features were random. When the p-value was small and the absolute value of the Z score was large (falling outside of the confidence level), the null hypothesis was rejected. If the Moran's I value was greater than 0, the set of features exhibited a clustered pattern. If the value was less than 0, the set of features exhibited a dispersed pattern. The simplified mathematical expression of the Moran's I statistic is presented in equation 1.

$$I = \frac{n \sum_i \sum_j W_{ij} (X_i - \bar{X}) (X_j - \bar{X})}{\sum_i \sum_j W_{ij} \sum_i (X_i - \bar{X})^2} \quad (1)$$

Where

I = Morans's Index

X_i = value of the target feature

X_j = value of the neighbor feature

\bar{X} = mean value

W_{ij} = weight for that pair

n = number of features

In order to estimate the spatial autocorrelation of deforestation we calculated the Moran's I statistic considering several threshold distances. Features outside the specified cutoff distance were ignored. For each increment of deforestation between 2000 to 2008 (i.e. 2001, 2002, ...,

2008) we calculated the Moran's I for 5 km, 10 km, 15 km, and 20 km, using the area deforested in the cell as the weighted field.

For each cell with deforestation higher than zero, the Moran's I statistic first counted the number of neighbor cells inside the buffer distance (i.e. 10 km). Next it calculated for each pair of features inside the region, the difference between the feature values (the area of deforestation in each cell) and the mean value for all features. This result was then multiplied with the weight which was the size of the deforested area in this case, to calculate the cross-product, and then summed. Finally, the result was divided by the weighted cross-product to get the radius.

3.2.2 Mapping the Hot and Cold spots using Getis-Ord G_i^* (G-statistics)

We used the Getis-Ord G_i^* to identify the Hot and Cold spots of deforestation in the Calha Norte region. The Getis-Ord G_i^* statistics told where features with either high or low values were cluster spatially, looking at each feature within the context of neighboring features (Mitchell, 2005). To be a statistically significant Hot spot, a feature would have to have a high value and be surrounded by other features with high values as well. The sum of the feature and its neighbors was compared to the sum of all features. The local sum for a feature and its neighbors was compared proportionally to the sum of all features. When the local sum was much different than the expected local sum, and that difference was too large to be the result of random chance, a statistically significant Z score resulted.

The Getis-Ord G_i^* statistics returned for each feature in the dataset is a Z score. For statistically significant positive Z scores, the larger the Z scores, the more intense the clustering of high values (Hot spot). For statistically significant negative Z scores, the smaller the Z score, the more intense the clustering of low values (Cold spot) Mathematical formula is presented in equation 2 and more detail about this index can be found in Mitchell (2005).

$$G(d) = \frac{\sum_i \sum_j w_{ij} (x_i \cdot x_j)}{\sum_i \sum_j (x_i \cdot x_j)} \quad (2)$$

Where

$G(d)$ = General G-statistic, for a distance (d)

x_i = value of the target feature

x_j = value of the neighbor feature

w_{ij} = weight for that pair of features

We calculated the Getis-Ord G_i^* statistics using the area deforested in the cell between 2000 and 2008, as the weight and the distance where the clustering presented high significance levels (calculated earlier with the Moran's I tool). This radius was defined empirically as the distance at which spatial autocorrelation is highest.

4. Results

4.1 Geography and annual rates of deforestation

The area deforested in the Calha up until 2008 was 11,661 km² (**Figure 2**). The majority of the deforestation (74%) was concentrated in the non-protected areas and 20% in settlements in the south of the study area. The remaining 6% of deforestation occurred in the protected areas (3% in sustainable use areas, and 3% in the others types of protection).

The non-protected areas experienced the highest average annual rate of new deforestation, which was about 151 km² every year. In the settlements, the average rate of deforestation was 10 times lower. In the protected areas the highest rate was concentrated in the sustainable use conservation units with an average of 11 km² of deforestation per year (**Figure 2**).

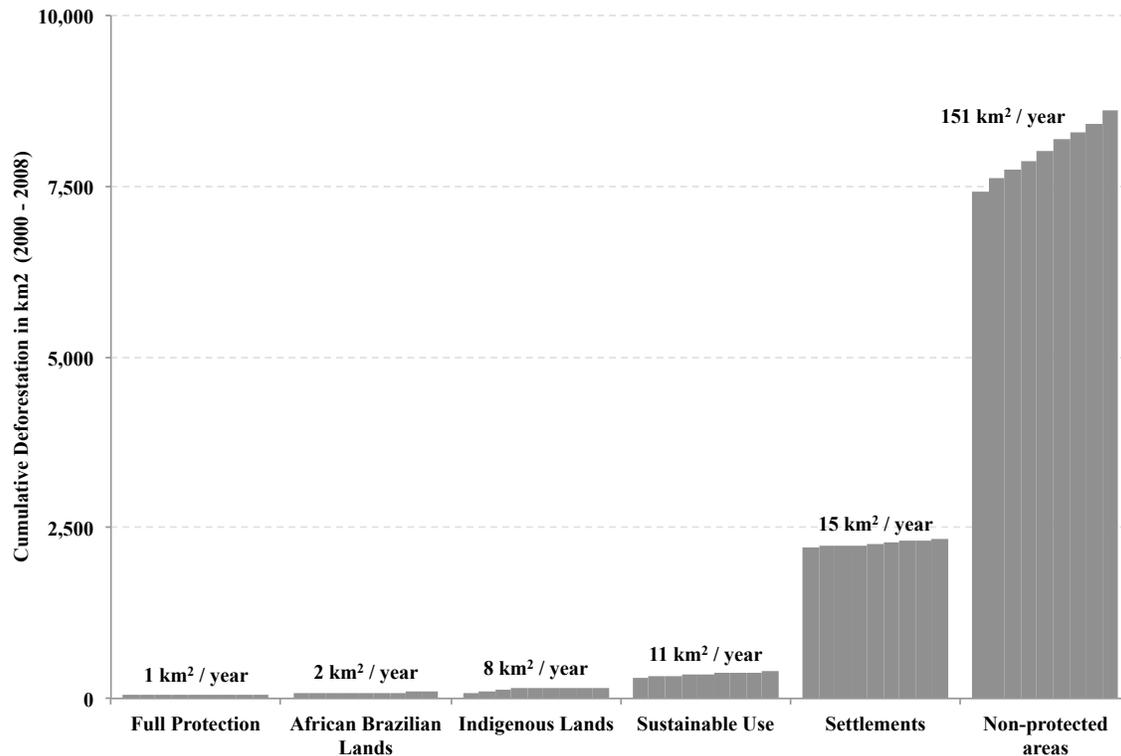


Figure 2. Cumulative deforestation from 2000 to 2008.

4.2 Spatial patterns of deforestation

4.2.1 Spatial autocorrelation

On average the peak of clustering of the new deforestation was concentrated at 10 kilometer with a mean Moran's I value of 0.07 and a Z-score of 112.33. This result indicated that the deforestation polygons were statistically auto-correlated within this 10 kilometer zone.

4.2.2 Hot and Cold spots

The results of the Getis-Ord Gi* statistics showed that between 2001 and 2008, the Hot spots of deforestation moved mostly from east to west in the Central-South area of the Calha Norte region (**Figure 3**). When we overlapped the eight Hot/Cold spot maps produced, we identified two areas that were consistently classified as Hot or Cold spots. The Cold spot persistence areas were located in the Central region of the Calha Norte, near to the settlement areas, and the Hot spot persistence areas were located close to the Paru State Forest.

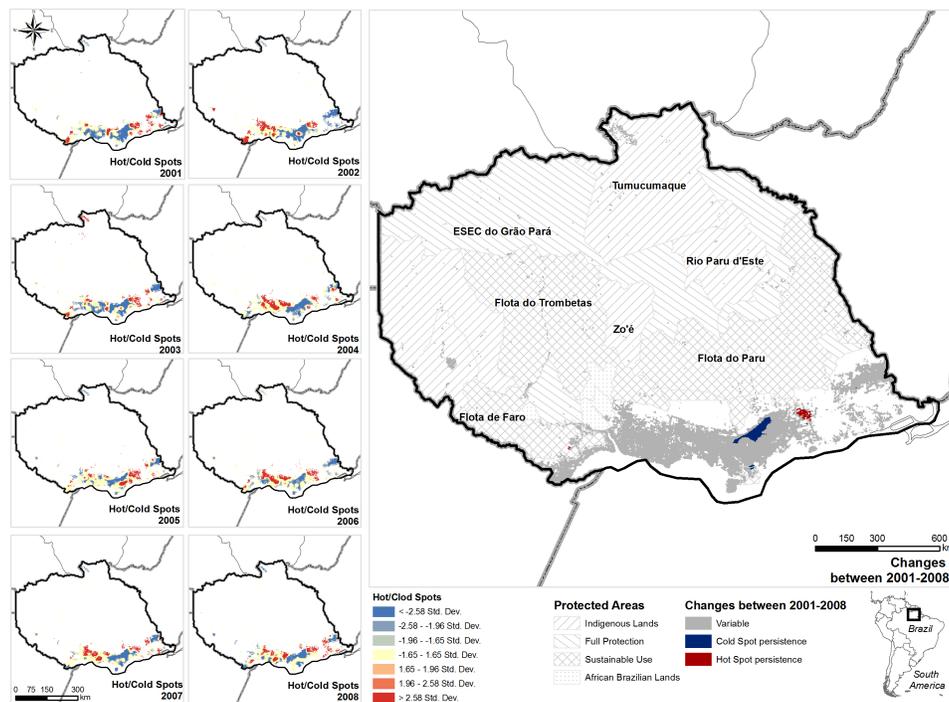


Figure 3. Hot/Colds spots mapped in the study area from 2001 to 2008.

5. Discussion and conclusions

In this paper we analyzed the temporal and spatial dynamics of deforestation in the Calha Norte region until 2008. We identified that deforestation in the study area follows a pattern. The results indicated that more than 94% of the deforestation occurred outside the protected areas at an annual rate of 151 km² per year. Spatially, the increment of deforestation was statistically autocorrelated at distances of 10 km. The Hot and Cold spots identified were localized in the Central-South regions, with two main regions identified as persistent Hot spots and persistent Cold spots.

The method used in this study has a strong potential to be replicated in others regions in the Brazilian Amazon. We showed that increments of deforestation were spatial autocorrelated around clusters of cells with high and low rates of deforestation. The information provided with our approach could help to improve the surveillance of these areas. Although, future studies should explore the underlying causes of the deforestation and its persistence in the Hot spots.

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