Deforestation in the Legal Amazon: The Impacts of Human Action on the Regional Climate Scenario

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Abstract

The Legal Amazon was established by the Brazilian government in 1953, in order to plan and provide for the social and economic development of the Amazon region. This is a region of great importance due to the maintenance of biogeochemical cycles that the forest exercises and for being a biodiversity hotspot. Amazon has been suffering from an intense and rapid change in land use and coverage, where deforestation and forest fragmentation stem from the agriculture expansion and wood exploitation. Therefore, this work aimed to identify and measure changes in the hydrological cycle and in the dynamics of climatic elements caused by human activities in the Legal Amazon. In addition, predictions of land use and land cover conditions were made for the years 2040, 2070 and 2099 allowing the knowledge of the level of long-term deforestation in this area. To achieve the objective, data from the study area were collected and standardized. The data was processed and compared, using the Land Change Modeler and Earth Trends Modeler modules. The results obtained by the modules are interrelated. Hydrological and climatic variables are impacted by changes in land use and coverage, from the expansion anthropic activities over natural vegetation, mainly in the area defined in this study, where the direct impact on NDVI is evident. These results corroborate to show that, in the legal Amazon, the forest has a direct influence on the climate. In this context, the failure to adopt conservationist practices and contain the natural forest suppression, increases deforestation, causing changes in the variables studied, tending to a worsening of climatic conditions.

Introduction

The Brazilian government through Law 1,806, on January 6, 1953, in order to plan and promote the social and economic development of the region, instituted the Legal Amazon. Its territorial limitation is based on a socio-political bias, housing the Brazilian Amazon biome and part of the Cerrado and Pantanal biomes being composed of nine states (IBGE, 2020).

Although it is a place of great importance due to the maintenance of biogeochemical cycles and because it is a biodiversity hotspot, this area has been suffering from an intense and fast change in land use and coverage. Deforestation and forest fragmentation, stemming from agriculture expansion and wood exploitation, have further driven this process of change (FARIAS et al., 2018; NASCIMENTO et al., 2019; MONTIBELLER et al., 2020). The changes that have occurred may result in changes in carbon storage, forest' microclimate, biodiversity conservation, erosion, floods, flows reduction, among others (BROADBENT et al., 2008; LAURANCE et al., 2011; POORTER; 2015; JUSYS, 2016).

According to Ferreira and Coelho (2015) and Farias et al. (2018), the deforestation process in the Legal Amazon is closely linked to market factors, such as changes in the agricultural commodities' price and government public policies. Thus, the deforestation scenario follows the Brazilian political and economic panorama.

Deforestation also interferes with energy and water exchanges between forests and the atmosphere, modifying albedo, roughness and evapotranspiration. Less evapotranspiration means a lower heat flow, which is compensated by a higher sensitive heat flow, tending to increase the temperature close to the surface. Regarding the Amazon region, studies agree that, in general, deforestation raises the temperature (LEJEUNE et al., 2014).

Furthermore, it is expected that with decreasing evaporation, the precipitation also decreases, due to this is caused the local water vapor released by the forest and transported by the movement of air masses (ROCHA et al., 2017). This movement from one region to another, can directly influence the hydrological regime of an area (ALVES et al., 2018) causing changes at the local, national, and global levels (ALMEIDA et al., 2016). In the Amazon region, the air mass occurs due to a high process of forest' evapotranspiration, being of great importance in the transport of humidity to the other regions of Brazil. (FARIAS et al., 2018).

The precipitation, besides being one of the main climatic elements in tropical regions, is what best characterizes the climatic variability and influence the behavior of other atmospheric variables (humidity, temperature, among others) (SOUSA et al., 2015). According to Almeida et al. (2016), forests have a great influence on the climate and, in turn, are sensitive to climate change. Studies argue that the Amazon rainforest can be directly affected by climate change and may suffer consequences (MARENGO; SOUZA JR., 2018; AMARAL and SILVA et al., 2020).

Climatic and environmental factors, such as temperature, precipitation, and evapotranspiration, together with the Normalized Differences Vegetation Index (NDVI), have been used to correlate, in a spatial and temporal way, the vegetation level (LAMCHIN, et al. 2018). According to Farias et al. (2018), the formation of rains is directly linked to natural vegetation, thus, deforestation has an impact on water loading by air masses.

Climate change is already happening, generating warming and impacts on a global scale. In the Amazon region, the warming between 1949 to 2017 ranged from 0.6 to 0.7°C, which was greater in recent decades. According to the Intergovernmental Panel on Climate Change (IPCC), an increase in air temperature above 4°C and a reduction in precipitation of up to 40% are expected by the end of the 21st century (MARENGO; SOUZA JR., 2018).

With the sudden environmental changes, the interest in monitoring ecosystems and understanding these changes has grown considerably (ALLER et al., 2019). Studying the impacts of human activities on the forest' complex climate system, especially in tropical regions, is important to support decision-making regarding conservation strategies, management, and public policies insertion. Thus, knowing the trends of climatic variables and how they relate, can help to understand the intensity of human interference in the climate (ALMEIDA et al., 2016).

Given the above, this work aimed to identify and measure changes in the hydrological cycle and in the dynamics of climatic elements (humidity, atmospheric pressure, and temperature) caused by anthropogenic activities in the Legal Amazon. In addition, predictions of land use and land cover conditions were made for the years 2040, 2070 and 2099 allowing knowledge of the level of long-term deforestation in this area.

Materials And Methods

Figure 1 shows the methodology proposed in this work.

2.1 Study area

The study area comprises the Brazilian Legal Amazon (Figure 2). It encompasses the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Roraima, Rondônia, Tocantins, in their entirety, and part of the state of Maranhão, with an area of approximately 5.1 million km², which corresponds to about 59% of the Brazilian territory (SUDAM, 2020). The Legal Amazon has in its extension the Amazon rainforest, as the predominant biome, and part of two other Brazilian biomes (Cerrado and Pantanal).

Legal Amazon is in the equatorial region, has a hot and humid climate, where average annual temperatures are around 25°C, ranging from 8 to 28°C. The extremes occur only in a few areas (CARVALHO et al., 2020). Average rainfall is approximately 2,300 mm per year, in some regions reaching an annual total of 3,500 mm (FISCH et al., 1998). In other regions, precipitation is around 1,100 mm, with a longer dry period similar to the Brazilian semiarid region (VALE JÚNIOR, 2011). About 50% of the total precipitation comes from the evapotranspiration of the Amazon basin itself (ROCHA et al., 2019).

The Amazon region has diversified vegetation, with variations of vegetation types in savannahs, savannas, and dominance of the most varied forests that are closely associated with climate and soil. (VALE JÚNIOR, 2011).

Regarding Legal Amazon' relief, 7% of the area is lowland and 74% is formed by an irregular relief, of which 16% is rugged, more vulnerable to the erosion risk. (IBGE, 2009). Due to the extension of the area and countless factors associated with the soil formation process, several soil classes are found, presenting characteristics such as: low phosphorus content; high acidity and saturation by aluminum; low cation exchange capacity; poverty in micro and macronutrients; among others (VALE JÚNIOR, 2011).

2.2 Database, collection, standardization and processing

Table 1 shows the time series, as well as the source and resolution of the data used. They were acquired from official sources and freely accessible.

To data standardization, software ArcGis® was used, on ESRI's ArcMap platform version 10.6.1. This step consisted of resizing the database, using the lowest resolution file as a reference (AMARAL and SILVA et al., 2020) and adoption of a cartographic projection system that presented a low level of deformation within the studied area (South America Albers Equal Area Conic) (LUMBAN-GAOL et al., 2019). It should be noted that the data were standardized considering the parameter of lower spatial resolution as a reference in order to allow comparison and analysis of the bases included in this study.

After standardization, the data were directed to processing in the Idrisi software Selva® 17.0, Clark Labs, where two modules were worked on: Land Change Modeler (LCM) and Earth Trends Modeler (ETM). They aim to study changes in land cover and variations within a series of temporal data, respectively (EASTMAN, 2012).

LCM is an Idrisi software module that provides a robust set of tools for analyzing land cover changes, predicting future scenarios and the specific needs for biodiversity conservation in the face of changes (EASTMAN, 2012). LCM module is based on the analysis of artificial neural networks, having advantages over traditional computational methods (MEHRABI et al., 2019).

In this study, the LCM was used to compare changes in the levels of natural vegetation between 1985 and 2018 (year on year), calculating the difference between the areas of the categories "Forest" (areas of natural vegetation) and "Non-forest" (areas with the presence of anthropic activity). From this calculation, it was possible to have knowledge of the deforestation trend within the Legal Amazon, in the adopted period, and further analysis of these data along with the processing applied to environmental variables.

The processing step also relied on the use of the ETM interface. It is a tool that allows the modeling and analysis of earth trends and the dynamics of environmental phenomena, based on data from time series of images (EASTMAN, 2012).

The ETM was used to analyze the hydrological and environmental variables (precipitation, temperature, soil moisture, evapotranspiration, specific humidity, atmospheric pressure and NDVI). This analysis sought to understand the behavior of these variables within the adopted period (1985 - 2018) and the existing correlation between them (Correlation test) (SANTOS and TOLEDO FILHO, 2014). Still, we sought to relate the trends presented by the environmental variables (Mann-Kendall test) and the change in land use and coverage (GÜÇLÜ, 2018).

Mann Kedall test is a non-linear trend indicator. Used to measure whether the trend is positive (increasing) or negative (decreasing), with its variation between -1 and +1, where the negative and closest to one, means that the trend is decreasing continuously and the closest the positive extreme, indicates an upward trend. The zero value indicates that there is no consistent trend (RAHMAN; DAWOOD, 2017).

As a form of complementary analysis, the LCM was used to generate information about the future conditions of the study area, and the proportions of deforestation in the Legal Amazon in 2040, 2070 and 2099, with HARD predictions, since these are for the distant future. The years were selected because, according to the Brazilian Panel on Climate Change - PBMC (2013), changes in future climatic conditions are expected for these three periods, reflecting changes in the current state of land use and coverage.

In this stage, the years 2005 and 2014 were used to calibrate the model, and the year 2018 for its validation, where the predicted map was compared with the map, from the same year, made available by an official organization (MapBiomas). For comparison, the CROSSTAB algorithm was applied, obtaining the value of the Kappa index, used to validate the model produced (LANDIS; KOCH, 1977).

Table 2 shows the variables used to induce change, as well as the period adopted, data source, resolution, and the behavior (static or dynamic).

The methodology addressed in this work is similar to that applied by Amaral e Silva et al. (2020), since, as done by the author, we sought to study the relationship between environmental variables and the conditions of land use and coverage, corroborating with studies that claim that, in this area, the forest has a direct impact on climate conditions. Different from the study carried out by the author, other climatic variables were incorporated, in order to deepen the analyzes already carried out, generating results of greater accuracy and strengthening the aspect advocated. In addition, different periods were adopted, and other change-inducing variables were inserted in the process of predicting future conditions, allowing to obtain data closer to the real and with better quality of information.

Results

The Amazon region, throughout its history, has suffered from the most diverse forms of environmental degradation, with deforestation being the best known (REGO et al., 2011). Due to the regional development process of the Eastern Amazon, the forest area transformed over the years in this region, an extensive area was formed with a rapid decline in forest cover (FARIAS et al., 2018). Thus, the results presented will have the representation of this delimited area.

In the LCM module, analyzes of land use and land cover changes were carried out between 1985 and 2018. Figure 3 shows the maps of the temporal space evolution of these changes in the region of the Legal Amazon, and the deforested areas of the years 2005 and 2018.

It is noticeable the advance of anthropic activity areas over forest between 1985 and 2018, mainly in the delimited area. Areas of anthropic action increased by about 227%. The deforested areas of the years 2005 and 2018 are compatible with the non-forest areas of the same years, evidencing that the advance of the areas of anthropic action occurred due to deforestation.

To verify the trend in relation to the variables precipitation, temperature, soil moisture, evapotranspiration, specific humidity, atmospheric pressure and NDVI, in the study area, mainly in the delimited area, maps were created from the application of the Mann Kendall test, in the ETM module.

Figure 4 shows the maps referring to the trends of hydrological and climatic variables are presented. The results corroborate those obtained in the study carried out by Amaral and Silva et al. (2020), where the increase in anthropic activities, implied changes in the environmental/climatic variables, concluding that the forest area has a direct influence on the local climate.

It was found that in most of the delimited area, the temperature varied proportionally to the anthropic action, while NDVI, precipitation, specific humidity, evapotranspiration and soil moisture were inversely proportional, and the atmospheric

pressure showed positive and negative trend points in the area, with Mann Kendall values close to zero.

The delimited area is the place where the expansion of anthropic activities occurred more perceptibly with the replacement of natural vegetated areas. NDVI tends to decrease as well as the levels of rain, soil moisture, evapotranspiration, and soil moisture, while the largest part of the expanding area of anthropogenic activities the tendency was for an increase in temperature or constancy.

In order for the hydrological and climatic variables under study to be better characterized, the Correlation test was applied between NDVI and the other hydrological and climatic variables. This relationship was made with the NDVI, since this index enhances the green vegetation, capturing the chlorophyll content and the photosynthetic potential (SANTOS et. al., 2020). Thus, identifying the dynamics of vegetation and changes in land cover (DURAISAMY et al., 2018), as well as, allowing the identification of areas of suppression of vegetation and analyzing the correlations between deforestation and hydrological and climatic variables.

The correlation coefficient is a strong measure for analyzes of a linear relationship between variables (LAMCHIN et al., 2019), thus, complementing the Mann Kendall test. Figure 5 shows the maps produced after applying the correlation test.

Analyzing the area delimited on the maps, it is possible to observe that the NDVI, in most of the area, has a strong positive correlation with precipitation, specific humidity, evapotranspiration and soil moisture, indicating that these variables have a directly proportional behavior. As for the correlation between NDVI and temperature, it was classified as strongly negative, indicating that the variables are inversely proportional, varying non-linearly. Regarding atmospheric pressure, very weak correlations were obtained.

The predictions of future scenarios for the years 2040, 2070 and 2099, in the LCM module, were performed after model calibration and validation, where the Kappa index obtained was 0.83. According to Landis and Kouch (1977), the strength of agreement less than 0.00 is insufficient; 0.00-0.20 is low; 0.21-0.40 is reasonable; 0.41-0.60 is moderate; 0.61-0.80 is substantial; and 0.81 to 1.00 almost perfect, so the value found in the index can be interpreted as excellent.

The prediction scenarios were based on the Brazilian Panel on Climate Change - PBMC (2013), where future changes in climatic conditions are expected, due to changes in land use and coverage. Figure 6 shows the prediction maps, which focused on human activities, since the increase in these areas is caused by the suppression natural vegetation areas.

With the realization of the predictions for the years 2030, 2070 and 2099, it was found that the anthropic areas increased by about 356%, 485% and 567%, respectively, in relation to the year 1985, now representing approximately 24, 31 and 35% of the total area of the Legal Amazon.

Discussion

The results obtained by the LCM and ETM modules are interrelated. Hydrological and climatic variables are impacted by changes in land use and coverage, from the expansion of areas where there are human activities on natural vegetation.

It was found that, with the increase in deforestation, within the period adopted in this study, mainly in the delimited area, there was a significant reduction in native forest areas, with a tendency to reduce hydrological and climatic variables, such as NDVI, precipitation, soil humidity, evapotranspiration and specific humidity, and gradual increase in temperature.

Delazeri (2016), from a study addressing deforestation in the Legal Amazon, the author found that the advance of deforestation in the region is intensified by the advance of the agricultural frontier, in addition to socioeconomic changes, loss of biodiversity, reduction in the provision of ecological services and climate change.

Climatic changes are related to the expansion of anthropic actions since it generates greenhouse gas emissions, from activities such as burning, deforestation, formation of urban heat islands, among others (BENATI; SILVA, 2019). Due to this direct interference in the balance of the earth's radiation, it can result in changes in the climatic system (MOLEN et al., 2011).

According to Benati e Silva (2019), with the increase in the global atmospheric concentration of carbon dioxide, the average global temperature tends to increase. In addition, changes in land cover have an effect on albedo, contributing to changes in liquid radiation (MOLEN et al., 2011).

The change in albedo associated with changes in land cover and temperature can cause modification in the formation of clouds, as this is connected to water vapor and sensitive heat on the surface, which are associated with humidity and energy exchange (MOLEN et al., 2011). According to Farias et al. (2018), the formation of rains is directly associated with the level of natural vegetation, thus, deforestation has an impact on the water loading by the air masses, since the water vapor released from the forests comes from the process of evapotranspiration (ROCHA et al., 2017).

Thus, it is expected that with the reduction of evapotranspiration, precipitation will also decrease, due to the fact that it originates from the local water vapor released by the forest and transported by the movement of air masses (ROCHA et al., 2017). Moreover, a smaller evaporation means a lower heat flux, which is compensated by a sensible heat flux higher, tending to increase the temperature near the surface (LEJEUNE et al., 2014).

The Amazon region, due to its high solar incidence and water availability, interferes in the local, regional and global climate. This interference is the result of convective processes and evapotranspiration, however, the rainfall regime in the Legal Amazon region is heterogeneous, due to the influence of different meteorological systems and climatic variability. (TOSTES et al., 2017).

The reduction of the pluviometric regime has the consequence of an increase in the dry period, changes in rainfall, such as fluctuations in the rainy season and an increase in intense rains, drastically affecting the transport of moisture provided by the forest to the regions of Brazil and other parts of South America (SANTOS et al., 2017).

The application of the Mann Kendall and Correlation statistical tests showed that the advancement of anthropic activities has a direct impact on NDVI, due to the reduction of vegetated area, resulting in changes in hydrological and climatic variables.

Zhang and Zhou (2011), analyzing changes in precipitation intensity applying the Mann Kendall non-parametric statistical test to quantify the direction and magnitude of the trend of the raw data. Kumar et al. (2019) used the correlation coefficient seeking to define the strength and direction of the linear relationship between two random variables.

The results obtained in the trend analysis (Figure 4) show that the advancement of anthropic action activities, especially in the delimited area, has a direct impact on NDVI, causing changes in hydrological and climatic variables, which are confirmed through the application of Mann Kendall and Correlation statistical tests (Figure 5). Corroborating with the study by Amaral e Silva et al. (2020), where affirms that changes in NDVI directly impacted on climatic conditions, modifying the natural levels of rainfall and temperature, proving that the suppression of the vegetation cover, according to its dimension, can cause climatic changes at the local, national or global level.

According to Lejeune et al. (2015), the forest area should drastically decrease in the coming decades due to changes in land use and occupation, corroborating with the results obtained in this study (Figure 6). According to the Brazilian Panel on Climate Change - PBMC (2013), if deforestation conditions are maintained, it is expected that in the Amazon region there will be a 10% reduction in rainfall distribution and an increase of 1 to 1.5°C by 2040, reduction of 25 to 30% in the

rain and increase between 3 and 3.5°C between the period of 2041-2070, and reduction of the rains of 40 to 45% and increase of 5 to 6°C in the temperature at the end of the century (2099).

The trend of increasing annual temperature in the Amazon region has been reported in other studies. For example, Gloor et al. (2015) found a spatial distribution of an increasing temperature trend. Almeida et al. (2017) studying 47 climatic seasons in the Legal Amazon, from 1973 to 2013, found that the minimum, maximum and average annual temperatures showed an increase trend of approximately 0.04°C per year. Carvalho et al. (2020) in a study in the Amazon region between 1982 to 2015, found a tendency for an increase in temperature, around 0.2 - 0.3°C per decade, in which the regions with the highest increase are found mainly in the southeast region of the southeast Legal Amazon, confirming the results obtained in this study.

According to Rabelo and Costa (2019), climatic variations, with extreme events, cause impacts and affect people and ecosystems, consequently affecting the economy. Thus, it is essential to apply impact mitigation measures, mainly through government actions. According to Bernardo (2017), the government has a fundamental role in combating global warming, where the elaboration of its public policies must take into account the effects of climate change, and the existing public policies must also be reviewed.

Mitigating measures must be adopted to reduce greenhouse gases, with improvements in carbon sinks, such as the control of deforestation and revegetation of exposed areas, with a view to reducing the impacts of climate change, and these must be well defined and properly applied to reduce and control environmental impacts on the environment or damage resulting from human actions (SILVA; FRANÇA, 2018).

Conclusions

The advance of anthropic activity over forest in the Legal Amazon, between the years 1985 and 2018, increased by about 227% causing higher deforestation levels. The advancement of anthropic actions would imply changes in the environmental/climatic variables, confirming the view that the forest area under study has control over the climate.

Temperature trend varied proportionally to the anthropic action, while the NDVI variables, precipitation, specific humidity, evapotranspiration, and soil moisture were inversely proportional, and the atmospheric pressure showed positive and negative trend points, with values close to zero.

The NDVI showed a behavior directly proportional to precipitation, specific humidity, evapotranspiration, and soil moisture, and inversely proportional to temperature.

It was found that with the prediction for the years 2030, 2070 and 2099, the anthropic areas would increase by about 356%, 485% and 567%, respectively, in relation to 1985.

The failure to adopt conservationist practices and to contain the suppression of the natural forest increases deforestation, causing changes in hydrological and climatic variables, tending to an aggravation of climatic conditions.

There are sustainable development plans and public policy actions to contain the advancement of areas of human action on areas of natural forest in the Legal Amazon. An example of this is the integrated plan of private banks, together with the government, which aims to contribute to sustainable development, intensifying measures to protect the Amazon rainforest and encouraging the population to adopt measures for sustainability.

Declarations

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- 48.

Tables

Table 1 - Data, period, data source and resolution of the data

Data	Period	Data source	Resolution
Atmospheric pressure	1985-2018	NASA	1:25km
Specific humidity	1985-2018	NASA	1:25km
Evapotranspiration	1985-2018	NASA	1:25km
Soil moisture	1985-2018	NASA	1:25km
Temperature	1985-2018	NASA	1:25km
Rain	1985-2018	NASA	1:25km
NDVI	1985-2018	NASA	1:5km
Land use	1985-2018	MAPBIOMAS	1:30m
Deforested areas	2005-2018	INPE	1:500m

Table 2 - Variables that induce change

Variables	Period	Agency	Resolution	Type
Railways	2019	MINFRA	1:5km	Static
Waterways	2014	ANTAQ	1:5km	Static
Highways	2017	FOREST-GIS	1:5km	Static
Agriculture	2018	MapBiomass	1:5km	Dynamic
Livestock	2018	MapBiomass	1:5km	Dynamic

Figures

Figure 1

Methodological flowchart.

Figure 2

Study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Land use and coverage in the Legal Amazon in 1985, 2005 and 2018. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Mann-Kendall test maps of the analyzed variables. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Maps of correlations between variables. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Land use and coverage in the Legal Amazon predicted for the years 2040, 2070 and 2099. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.