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Talita Oliveira Assis

Doctorate Thesis of the Graduate Course in Earth System Science, guided by Drs. Ana Paula Dutra de Aguiar, Celso von Randow and Carlos Afonso Nobre, approved in September 04, 2020.

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Ciência do Sistema Terrestre

Dr. Jean Pierre Henry Balbaud Ometto

Presidente / INPE / São José dos Campos - SP

(x) Participação por Video - Conferência

(x) Aprovado ( ) Reprovado

Dra. Ana Paula Dutra de Aguiar

Orientador(a) / INPE / SJCampos - SP

(x) Participação por Video - Conferência

(x) Aprovado ( ) Reprovado

Dr. Celso von Randow

Orientador(a) / INPE / São José dos Campos - SP

(x) Participação por Video - Conferência

(x) Aprovado ( ) Reprovado

Dr. Carlos Afonso Nobre

Orientador(a) / INPE / São José dos Campos - SP

(x) Participação por Video - Conferência

(x) Aprovado ( ) Reprovado

Dra. Erika de Berenguer Cesar

Convidado(a) / Lancaster University / Inglaterra - UK

(x) Participação por Video - Conferência

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Dra. Joice Nunes Ferreira

Convidado(a) / EMBRAPA / Belém - PA

(x) Participação por Video - Conferência

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São José dos Campos, 04 de setembro de 2020

Dedico à minha família e

às pessoas cuja oportunidade de estudar foi tirada.

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(*in portuguese*)

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ABSTRACT

In the last years, forest degradation in the Brazilian Legal Amazon has shown significant values, frequently higher than deforestation. From August 2006 to July 2018, the degraded area totaled 191,632 km², representing 2.4 times the 89,501 km² deforested in the same period. The impacts of degradation include changes in the forest structure, carbon stocks, and biodiversity loss, affecting the CO_2 balance and future climate changes. This thesis investigates the factors underlying the Spatio-temporal distribution of forest degradation in this region in recent years and how they impact CO_2 balance in the region. Droughts and deforestation are some of the main factors linked to forest degradation. Then, we analyzed how the relationship between these factors and forest degradation evolved during this period by analyzing three indicators: water deficit anomaly indicator, historical clear cut deforestation indicator, and protected areas indicator. We also analyzed temporal trajectories of forest degradation from August 2006 to July 2016 in the Brazilian Amazon. We assessed their impact on the regional carbon balance, combining the degradation process with deforestation-related processes (clear-cut deforestation and secondary vegetation dynamics), using the spatially-explicit INPE-EM carbon emission model. Finally, we explored socio-economic and environmental factors that influence forest degradation spatial distribution and project scenarios of degradation and CO_2 emissions for the Brazilian Amazon. Our results pointed out that 80% of the degradation events occur in areas classified as drought condition areas during the driest years. In contrast, forest degradation in these areas does not exceed 50% when considering the entire period. On the other hand, the relationship between degradation and historical deforestation were, on average, 67% during the whole period. Additionally, our results also show that, on average, 25% of the degradation occurred in Indigenous Territories and 9% in Conservation Units. The trajectory analysis showed that 13% of the degraded area ended up being cleared and converted in the period, and 61% of the total degraded area experienced only one event of degradation throughout the whole period. Net emissions added up to 5.4 Gt CO_2, considering the emissions from forest degradation and deforestation, absorption from degraded forest recovery, and secondary vegetation dynamics. The results show an increase in forest degradation's contribution to net emissions towards the end of the period, related to the decrease in clear-cut deforestation rates, decoupled from the forest degradation rates. The spatially-explicit model allowed us to explore socio-economic and environmental factors that influence forest degradation spatial distribution and project future scenarios of degradation and CO_2 emissions to the Brazilian Amazon. We built sustainable and fragmentation land use scenarios and estimated their impacts on CO_2 emission. At the end of the simulation, most of them presented a portion of up to 10% of forest degradation. However, in the sustainable scenario, it was still possible to observe intact forest regions, especially in eastern Amazonas. Our results also showed that while net CO_2 emissions from 2019-2050 added up 0.74 Gt CO_2 in a sustainable scenario, in a fragmentation scenario, this value reached 22.63 Gt CO_2.

Keywords: Fire. Logging. Droughts. Deforestation. Modeling.

DEGRADAÇÃO FLORESTAL NA AMAZÔNIA BRASILEIRA: PADRÕES ESPAÇO TEMPORAIS, FATORES RELACIONADOS E EMISSÕES DE CO_2

RESUMO

Nos últimos anos, a degradação florestal na Amazônia Legal brasileira tem apresentado valores significativos, muitas vezes superiores ao desmatamento. De agosto de 2006 a julho de 2018, a área degradada totalizou 191.632 km², o que representa 2,4 vezes os 89.501 km² desmatados no mesmo período. Os impactos da degradação incluem mudanças na estrutura da floresta, nos estoques de carbono e perda de biodiversidade e também podem afetar o balanço de CO_2 e impactar as mudanças climáticas futuras. Esta tese tem como objetivo investigar os fatores relacionados à distribuição espaço-temporal da degradação florestal nesta região nos últimos anos e como eles impactam o balanço de CO_2 na região. As secas e o desmatamento são alguns dos principais fatores ligados à degradação florestal. Sendo assim, foi analisada como a relação entre esses fatores e a degradação florestal evoluiu durante esse período, analisando três indicadores: indicador de anomalia de déficit hídrico, indicador de desmatamento histórico por corte raso e indicador de áreas protegidas. Também foram analisadas trajetórias temporais de degradação florestal de agosto de 2006 a julho de 2016 na Amazônia brasileira e avaliamos seu impacto no balanço de carbono regional, combinando o processo de degradação com processos relacionados ao desmatamento (desmatamento por corte raso e dinâmica da vegetação secundária), usando o modelo espacialmente explicito de emissão de carbono INPE-EM. Finalmente, foram explorados os fatores socioeconômicos e ambientais que influenciam a distribuição espacial da degradação florestal e projetados cenários futuros de degradação e emissões de CO_2 para a Amazônia brasileira. Os resultados apontaram que, durante os anos mais secos da série histórica, 80% dos eventos de degradação ocorrem em áreas classificadas como de seca. Em contrapartida, a ocorrência de degradação florestal nessas áreas não ultrapassa 50% quando considerado todo o período de análise. Por outro lado, as relações entre degradação e desmatamento histórico foram, em média, 67% em todo o período. Além disso, também foi mostrado que, em média, 25% da degradação ocorreu em Territórios Indígenas e 9% em Unidades de Conservação. A análise da trajetória apontou que 13% da área degradada acabou sendo desmatada e convertida no período e 61% da área degradada total sofreu apenas um evento de degradação ao longo dos anos considerados. As emissões líquidas somaram 5,4 Gt CO_2, considerando as emissões da degradação e desmatamento florestal, absorção da recuperação da floresta degradada e dinâmica da vegetação secundária. Os resultados exibiram um aumento da contribuição da degradação florestal para as emissões líquidas no final do período, relacionada à diminuição das taxas de desmatamento por corte raso, desacoplada das taxas de degradação florestal. O modelo espacialmente explícito nos permitiu explorar fatores socioeconômicos e ambientais que influenciam a distribuição espacial da degradação florestal e projetar cenários futuros de degradação e emissões de CO_2 para a Amazônia brasileira. Foram construídos cenários de uso do solo sustentáveis e de fragmentação e estimamos seus impactos nas emissões de CO_2. Ao final da simulação, a maioria deles apresentava uma parcela de até 10% de degradação florestal. Porém, no cenário "sustentável", ainda foi possível observar regiões de floresta intacta, principalmente no leste do Amazonas. Enquanto as emissões líquidas de CO_2 de 2019-

2050 somaram 0,74 Gt CO_2 no cenário sustentável, no cenário de fragmentação esse valor atingiu 22,63 Gt CO_2.

Palavras-chave: Fogo. Exploração madeireira. Secas. Desmatamento. Modelagem.

LIST OF FIGURES

Pág.

LIST OF TABLES

LIST OF ABBREVIATIONS

AGB	Above Ground Biomass
AIC	Akaike information criterion
BGB	Below Ground Biomass
CLUE	Conversion of Land Use and its Effects Modeling Framework
CO_2	Carbon Dioxide
CRU	Climatic Research Unit
GHG	Greenhouse Gases
Gt CO_2	Gigatonnes of carbon dioxide
Ha	Hectare
INPE	National Institute for Space Research
IPCC	Intergovernmental Panel on Climate Change
JRA	Japanese reanalysis
Km^2	Square Kilometer
RCP	Representative Concentration Pathways
SSP	Shared Socioeconomic Pathways
Wm^{-2}	Watts per square meter

CONTENTS

Pág.

1 GENERAL INTRODUCTION

The Brazilian Legal Amazon has 5,217,423 km² and corresponds to 61% of the Brazilian territory. It is a mosaic of public and private lands in which multiple land uses compete for space (protected areas, agriculture, mining, etc.). The natural forest currently occupies around 80% of the area, mostly located in protected areas, including environmental conservation units and indigenous territories. This mosaic has been changing over time due to human actions and government policies implemented in the region. The process of socio-spatial formation in the Brazilian Legal Amazon is heterogeneous over time. Until the 1950s, human occupation occurred along the rivers, focused on extractive fishing, and along the highways, basically related to the practice of livestock (BECKER, 1997; TAVARES, 2011). Based on federal public policies in the 1960s and 1970s, the occupation was intensified in other areas, motivated by road infrastructure investments, rural settlement projects, and credit policies (AGUIAR; CÂMARA; ESCADA, 2007; TAVARES, 2011). In the 1970s, the First National Integration Plan and the policy were established to fill the "Demographic Emptiness," expanding the region's infrastructure, resulting, for example, in the construction of the Transamazonica highway. Since highways and rivers facilitate production outflow, connection to other markets, and migratory flows (BECKER, 2001; AGUIAR; CÂMARA; ESCADA, 2007), these government actions have changed the relationship of population and geographical space in the region. These changes intensified deforestation, forest degradation, economic exploitation, and land conflicts between indigenous, settlers, gold miners, and farmers.

From the 1980s, even with the creation and consolidation of settlement projects and the influence of the State, the national and international markets make the Amazon, especially the Eastern, become more associated with global economic dynamics (BECKER, 2004). However, in the 1990s, discussions about sustainable development and conservation gained strength in the political and social scenario, resulting in several public policies for land regularization and environmental protection in the Amazon, which were implemented in the 2000s (KOHLHEPP, 2002; VERÍSSIMO; COCHRANE; SOUZA, 2002).

Conservation units and indigenous territories compose the protected areas mosaic formed by these policies. They are a vital component of biodiversity conservation and have also become a key feature of global efforts to reduce carbon emissions from tropical deforestation and degradation. These areas are managed under a comprehensive range of governance regimes and include several processes driven by different legislations, theoretically, to achieve better ecological and social effects. In general, the Sustainable Use conservation areas allow occupation by local traditional populations and execution of economic activities based on ecosystem services, ecotourism, and the other types of labor. Meanwhile, in Strictly Use Conservation areas, no commercial activity is allowed (RYLANDS; BRANDON, 2005; NOLTE et al., 2013; THALER, 2017). Constitutional Right provided by the Brazilian Federal Constitution, Indigenous Territories are among the most important public areas and covers 22% of the Brazilian Amazon. These reserves aim to preserve indigenous communities' way of life and protect the forest against deforestation and infrastructure expansion (RYLANDS; BRANDON, 2005).

Besides, environmental issues that make the forest more vulnerable have gained notoriety, such as the increasing number of wildfires (BRANDO et al., 2020b) and higher frequency of extreme drought events (MARENGO et al., 2011). This complex scenario, concerning human actions and environmental issues, has resulted in native forest loss due to deforestation and forest degradation.

In the last years, forest degradation in the Amazon has shown significant values, frequently higher than deforestation (INPE, 2020). From August 2006 to July 2018, the degraded area totaled 191,632 km², representing 2.4 times the 89,501 km² deforested in the same period (INPE, 2020a). There are several definitions for forest degradation, reflecting different perceptions, objectives, values, and differences in forests' formation (FOLEY et al., 2005; SIMULA, 2009; THOMPSON et al., 2013; GHAZOUL et al., 2015). In general terms, forest degradation is the reduction of the forest's capacity to produce ecosystem services, such as carbon stocks, climate regulation, and biodiversity conservation, as a result of anthropogenic actions and environmental changes. It comprises the partial loss of the forest without converting it to other land cover types.

Forest degradation is spread in the forests worldwide due to unsustainable logging, fire, agriculture, invasive species, firewood gathering, and livestock grazing. In the Brazilian Amazon, this process mainly consists of a combination of logging and fire (NEPSTAD et al., 1999; GERWING, 2002; ASNER et al., 2006; COCHRANE; BARBER, 2009). Its impacts include changes in the forest structure (BARLOW; PERES, 2008) and in the carbon stocks (BERENGUER et al., 2014b; ANDERSON et al., 2015; RAPPAPORT et al., 2018; SILVA et al., 2018), and biodiversity loss (IPBES, 2019, BARLOW et al., 2016). Forest degradation can also affect the CO_2 balance and future climate changes (ARAGÃO; SHIMABUKURO, 2010; BACCINI et al., 2017; FARIA et al., 2017).

Several authors have proposed to account for changes in the CO_2 balance due to forest degradation (ANDERSON et al., 2015; AGUIAR et al., 2016; BACCINI et al., 2017; ARAGÃO et al., 2018), but there are still many uncertainties due to the lack of knowledge of this process. Understanding the degradation process and how it evolves over the years is, therefore, a key research gap and can assist in assessing its regional impacts. Kury (2016) identified trajectories from areas degraded in 2007 to describe whether these areas regenerated, suffered recurrent degradation, or were converted to clear cut deforestation. Pinheiro et al. (2016) and Alencar et al. (2011) also analyzed the behavior of degraded areas in local multitemporal analyzes. But there is a lack of knowledge of the temporal patterns of this degradation for the entire region.

Nepstad et al. (2006) and Soares-Filho; Rajão (2018) argue about the importance of conservation units and Indigenous Territories in controlling deforestation and forest degradation. Nevertheless, Kury (2016) and Walker et al. (2020) showed that these areas are not inaccessible for these process, which is still happening within its borders, influenced by human actions, in the case of deforestation, and also by climate extremes, social and environmental issues in the case of forest degradation. Land-use changes are also central factors in the degradation process (ARAGÃO et al., 2014). The fragmentation caused by deforestation exposes the forest along its edges (COCHRANE; BARBER, 2009; ALENCAR et al., 2015) to environmental and anthropic issues. But the degradation has been significant even in the period from 2010 to 2015 when the Brazilian Amazon experienced deforestation rates below 7000 Km^2 (INPE,2020; INPE, 2020a). Thus, it is important to assess the evolution of these relationships over the years.

The relation between extreme droughts and the occurrence of forest degradation in the Amazon has been increasingly important due to the rise in droughts frequency and intensity (MARENGO et al., 2011; DUFFY et al., 2015), and their impact on the forest. Although several studies point out the importance of this relationship (ARAGÃO et al., 2007; BRANDO et al., 2014; LENNOX et al., 2018), it is also important to evaluate how degradation and water deficit are associated with each other in non-drought years with and other factors linked to this process.

1.1 Goal, research questions, and objectives of the thesis

Considering the importance of forest degradation in the Brazilian Amazon and the knowledge gaps presented, the central goal of this thesis is to investigate the factors underlying the spatio-temporal distribution of forest degradation in this region in recent years, and how they impact CO_2 balance in the region.

In particular, this thesis aims at answering the following research questions about the forest degradation patterns:

(a) How is the spatial-temporal distribution of forest degradation related to water deficit in drought and non-drought years?

(b) How do past deforestation spatial patterns influence this distribution?

(c) How do protected areas have been affected by forest degradation?

(d) How much of degraded areas become clear-cut deforestation and how the combination of these two processes affects the biomass and CO_2 emissions?

(e) Which other socio-economic and environmental factors influence the forest degradation spatial distribution?

(f) Based on these factors, can we explore future scenarios of forest degradation CO_2 emissions?

To answer these questions, we organized the thesis around three specific objectives:

1. Quantify the relationships between forest degradation, droughts, deforestation, and conservation units (protected areas) in the Brazilian Amazon. This objective addresses questions (a), (b), and (c).

2. Analyze spatio-temporal trajectories of forest degradation recovery and conversion to other land uses in the region, and estimate their impacts on regional CO_2 emissions. This objective addresses the question (d).

3. Explore the spatial relationships of forest degradation and different socio-economic and environmental factors and project scenarios of degradation and CO_2 emissions. This objective aims at answering questions (e) and (f).

1.2 Structure of the thesis

This thesis is structured as a collection of three papers related to the degradation process. The first paper (Chapter 2) attends to the specific objective “1” presented above; the second paper (Chapter 3) covers the specific objective “2,”; and the third paper (Chapter 4) explores the specific objective “3”.

Chapter 5 is a complement of the “Discussion” presented in Chapters 2, 3 and 4, and address elements that need to be analyzed in an integrated way because they are common among all these Chapters.

Chapter 6 brings the general conclusions of this thesis, revisiting the objective and the research questions presented above.

2 EXPLORING THE RELATIONSHIP BETWEEN FOREST DEGRADATION AND DROUGHTS, DEFORESTATION, AND PROTECTED AREAS IN THE BRAZILIAN AMAZON

2.1 Introduction

Over the last decades, land conversion of native forest areas to soybean farms or cattle ranches, urban growth, extraction of mineral resources, and irregular land speculation and grabbing have taken place in Brazilian Amazon (PACHECO, 2009), resulting in significant forest loss. These actions are impacting global climate (MARENGO et al., 2011), reducing local biodiversity (BARLOW et al., 2016; PAIVA et al., 2020), and making the way of life of its traditional populations unviable (SIREN, 2007; ATHAYDE; SILVA-LUGO, 2018). Public policies were implemented, expanding law enforcement, such as monitoring the forest trough remote sensing satellites, land regularization initiatives, and the creation of new conservation units through protected areas governance (VERÍSSIMO; COCHRANE; SOUZA, 2002; NOLTE et al., 2013; THALER, 2017; PAIVA et al., 2020).

Despite the efforts toward forest preservation, large infrastructure projects, such as opening new and paving highways and building large hydroelectric dams, have further increased the environmental and social fragility of the biome, compromising the natural dynamics of the forest and also making it much more exposed to human actions (COCHRANE; BARBER, 2009; LAURANCE et al., 2015; MORAN, 2016). Forest degradation is one of the consequences of this process, and its annual values are frequently higher than the clear cut deforestation ones, totaling 205.611 Km² from August 2006 to July 2018 (INPE, 2020; INPE, 2020a). In the same period, the total clear cut deforestation area was 89.501 Km², 43.5% of the total forest degradation. There are diverse definitions of forest degradation reflecting different perceptions, objectives, values, and biophysical differences among forest formations (SIMULA, 2009; THOMPSON et al., 2013; GHAZOUL et al., 2015). In the Brazilian Amazon, forest degradation is primarily associated with logging and fire, or a combination of both (GERWING, 2002). Many authors aim to understand and measure these process (COCHRANE et al., 1999; NEPSTAD et al., 1999; ASNER et al., 2006; ARAGÃO;

SHIMABUKURO, 2010; ALENCAR et al., 2011; BERENGUER et al., 2014a, 2018a; SILVA et al., 2018) and their impacts in the biodiversity and carbon balance (NEPSTAD et al., 2008; BLANC et al., 2009; ANDERSON et al., 2015; LENNOX et al., 2018).

Although protected areas establish some form of spatial restrictions on land use and resource extraction, they are not impervious (WALKER et al. ,2020). Even though there is evidence of their effectiveness in reducing and controlling deforestation and degradation (NEPSTAD et al., 2006; SOARES-FILHO; RAJÃO, 2018), this is still happening within its borders, influenced by human actions, in the case of deforestation, and also by climate extremes, social and environmental issues in the case of forest degradation.

One of the most important factors related to forest degradation is drought (ARAGÃO et al., 2007; BRANDO et al., 2020). Dry conditions increase the flammability of the forest, making it more susceptible to fire. Besides, in extreme conditions, droughts can also increase tree mortality. In severe drought years, such as 2010 and 2015-2016 (LEWIS et al., 2011; JIMÉNEZ-MUÑOZ et al., 2016), the total annual degradation area exceeded 20,000 Km^2. However, there are no studies that quantify this relationship over the years, on a regional scale to understand how the relationship between forest degradation and dry conditions evolves over the years.

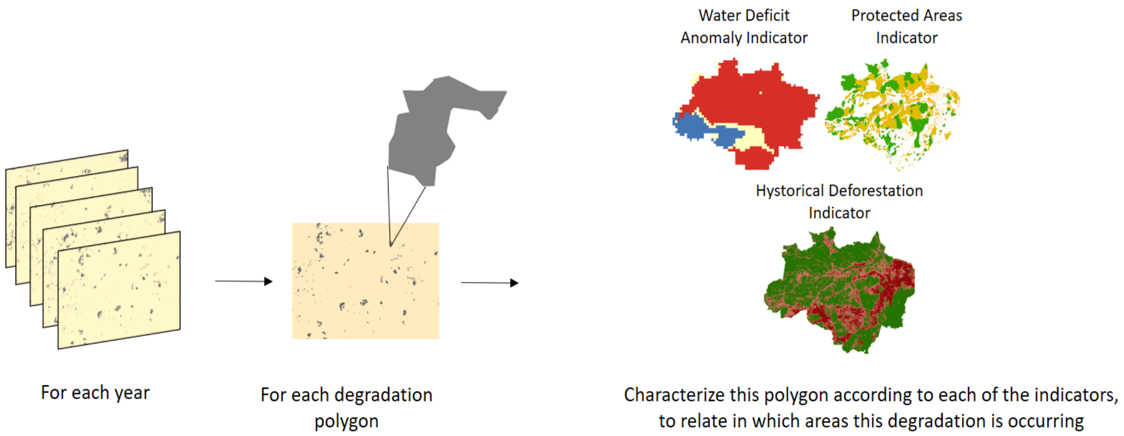
Land-cover changes are also central factors in the degradation processes. The fragmentation caused by deforestation exposes the forest along the edges (ALENCAR et al., 2015) and enhances the forest flammability, favors the increase in wind speeds, insolation rates, and fuel loads in those forest edges (COCHRANE; BARBER, 2009). In addition to the weakening of the forest edges, land use changes can be starting points for the fires that enter the forests (BARLOW et al.,2012). Aragão et al. (2018) discuss the drought-related fires in the Amazon and argues that the 2015 drought extended beyond the Arc of deforestation, and deforestation is losing its explanatory power over the variance of the absolute number of fire detections. But in recent years, we continue to observe high rates of degradation even in years without extremes droughts, leading to the need to understand these relationships from a multitemporal perspective.

In this Chapter, we quantified Spatio-temporal links between forest degradation in the Brazilian Amazon and water deficit, deforestation, and protected areas. We developed spatially-explicit indicators to characterize each forest degradation polygon in the period 2007 to 2018, as observed by the DEGRAD and DETER monitoring systems according to these indicators (INPE, 2020; INPE, 2020b).

2.2 Methods

To explore the relationship between degradation and different environmental- and human-driven factors of forest degradation, we constructed three indicators: i) water deficit anomaly indicator, ii) historical clear cut deforestation indicator, and iii) protected areas indicator (Figure 2.1) and verified how forest degradation is linked to each one of them, as described in the following sections.

Figure 2.1 - General methodology: For each year, we characterized the forest degraded areas according to three indicators: i) water deficit anomaly indicator, ii) historical clear cut deforestation indicator, and iii) protected areas indicator.



Source: Prepared by the author.

2.2.1 Degradation data

We used DEGRAD (INPE, 2020) and DETER B (DINIZ et al., 2015; INPE, 2020b) systems to obtain the polygons set, representing forest degradation occurred each year. DEGRAD system identifies forest exposed to fires and selective logging in the area of the Brazilian Legal Amazon monitored by PRODES system (INPE,2020a). The data are available with a minimum area of 6.25 ha. The mapping of degraded areas is carried out independently each year, disregarding the degradation polygons identified in the previous years of the analysis. Although our study covered the period from August 2006 to July 2018, DEGRAD has been discontinued, and the latest data is only available until August 2016. To complete the analysis period, we used the DETER B System.

DETER B maps deforestation and other changes in forest cover, and it is made available with a minimum size of 6.25 ha, allowing the establishment of a comparison criterion with the data generated by DEGRAD. To be compatible with the definitions of areas mapped by DEGRAD, we used the DETER B "Degradation" and "Burnt Scar" classes (INPE, 2020b). We also considered the period from August 1st of the previous year to July 31st for each year of analysis.

2.2.2 Water deficit anomaly

To analyze the extent and severity of drought events, we construct an indicator based on the maximum cumulative water deficit (MCWD) calculated for each year based on (ARAGÃO et al., 2007). We obtained MCWD from accumulating the differences between precipitation and evapotranspiration, for each month when this difference was negative (hence indicating water deficit months) and getting the most negative value of this cumulative indicator for each year. We used precipitation data from CRU-JRA, which is a composition between the interpolated observation data from the Climatic Research Unit (HARRIS et al., 2014) and the Japanese Reanalysis data (KOBAYASHI et al., 2015). For this, we adjusted the JRA reanalysis data to align with the CRU when there was data from the two datasets.

Monthly evapotranspiration used was fixed at 100 mm, as proposed by (ARAGÃO et al., 2007), which represents average evapotranspiration measured in different locations in the Amazon (VON RANDOW et al., 2004; DA ROCHA et al., 2009). Hence, MCWD was obtained from the accumulating monthly sums of the water deficit when precipitation falls below 100 mm.

We calculated a baseline running-mean for the 20 years preceding each year analyzed in question (1986 to 2005). Finally, the anomaly for each year (ΔMCWD) was calculated as

MCWD in the year minus the baseline mean for each grid point, with a resolution of 0.5 degrees.

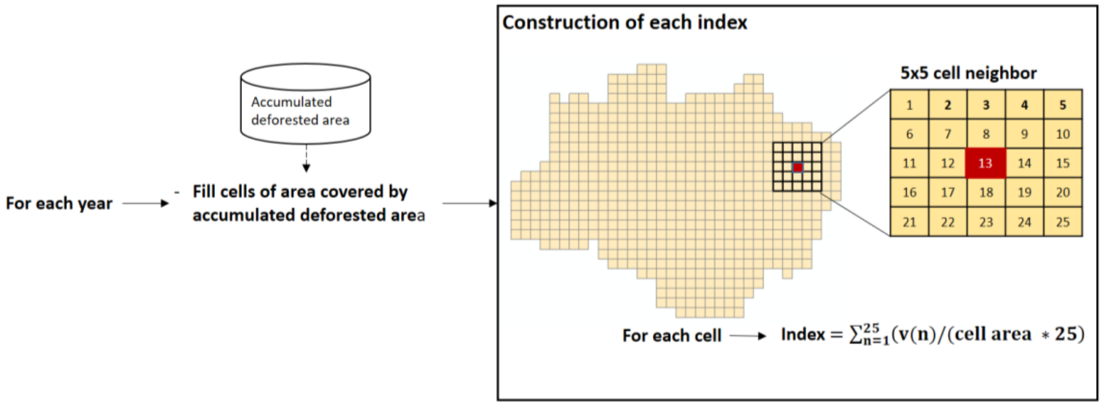
Finally, we classified the ΔMCWD anomalies into three ranges: i) drought conditions: ΔMCWD < -25 mm, ii) normal conditions: ΔMCWD between -25 and 25 mm and iii) wet conditions: ΔMCWD > 25 mm resulting in the water deficit anomaly indicator. The drought threshold of -25 mm reflects a level of water deficit where tree mortality was observed to significantly increase in forest inventory plots in the Amazon (LEWIS et al., 2011; ESQUIVEL-MUELBERT et al., 2019). The characterization of the degradation polygons in each year concerning the water deficit anomaly indicator received the value of class (drought, normal or wet conditions) of the grid cell containing the polygon in that year.

2.2.3 Historical deforestation index

We built a Historical Clear Cut Deforestation Indicator based on accumulated clear cut deforestation up to the previous year to understand how each degradation polygon is related to clear cut deforestation in its neighborhood. This indicator permitted us to analyze this link on a broader scale rather than a few meters around the degradation.

The deforestation data source was the PRODES System (INPE, 2020a) that identifies clear cut deforestation using satellite monitoring in the Brazilian Legal Amazon since 1988. It is considered by the Brazilian Government the official data for Amazon clear cut deforestation. Once an area is identified as deforested, it is not monitored in the following years, even when these areas are eventually abandoned, giving way to regeneration of secondary forests.

Figure 2.2 - Schematic graph of indicator construction.



Source: Prepared by the author.

For the development of this indicator, we used a spatial grid of regular cells of 5x5 Km^2 and performed the procedure illustrated in Figure 2.2. For each year of the analysis, we filled the cells with data of the area with historical clear cut deforestation. Then, for each cell, we summarized the data considering the neighborhood of a 5x5 cell to generate the deforestation indicator, given by Equation 2.1:

$$\sum_{n=1}^{25} v\,(n) \;\div\; (cell\,area \;\times 25) \qquad (2.1)$$

Where:

v (n) corresponds to the variable related to each of the indicators.

This indicator varies from 0 (100% of the 5x5 neighborhood cells with no historical clear cut deforestation) to 1 (100% of the 5x5 neighborhood cells with historical clear cut deforestation). We classified it into three ranges: i) 0%, ii) up to 50%, and iii) more than

50%. Each degradation polygons in each year received a Historical Clear Cut Deforestation Indicator according to the class of the grid cell containing the polygon.

2.2.4 Protected areas indicator

In this Chapter, we called Protected Areas the indicator composed by the Indigenous Territories (FUNAI, 2020; ISA, 2020) and Conservation Units (MMA, 2020). According to Sparovek et al. (2019), these areas cover 24.2% of all Brazilian territory.

We used the spatial intersection area between degradation polygons and each type of Protected Area mentioned above to estimate how the degradation is distributed over these areas. For each year of the analysis, we considered all protected areas existing in that year, divided into the categories above. For example, a Conservation Unit created in 2010 was found in all subsequent years, unless its existence is eventually legally revoked.

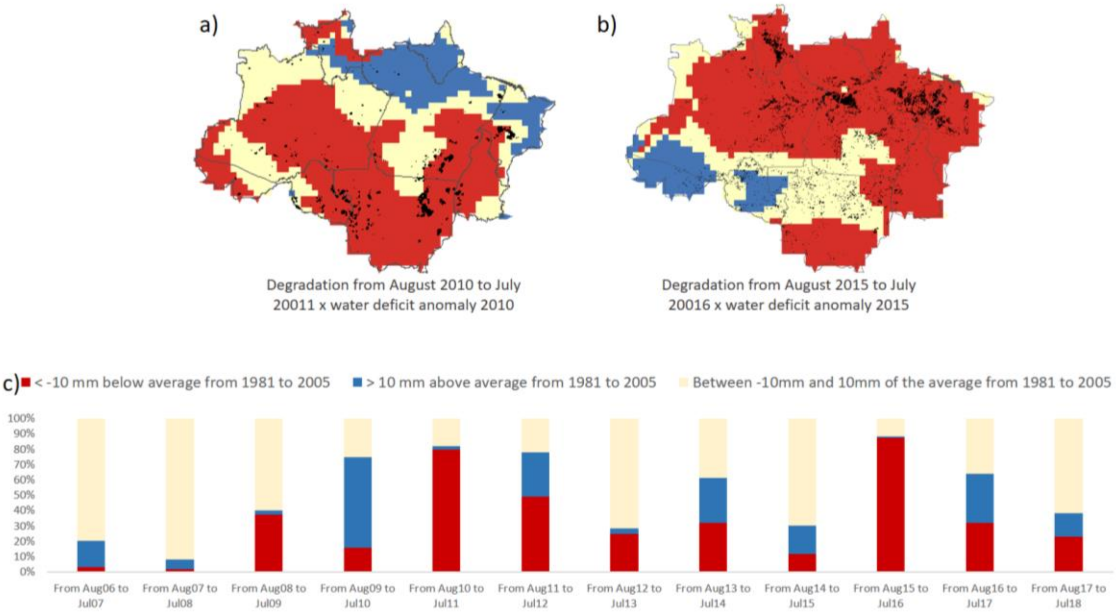
2.3 Results

2.3.1 Degradation and water deficit anomaly

Between 2007 and 2018, on average, 33.2% of forest degradation occurred in areas under drought conditions. This relationship reaches 79.7% and 87.5% of forest degradation between August 2010 to July 2011 and August 2015 to July 2016, respectively, when the region experienced extreme drought events in 2010 associated to anomalous warm waters in the North Tropical Atlantic Ocean and 2015-2016 linked directly to a strong El Niño episode in the Equatorial Pacific Ocean. The maps in Figure 2.3a and Figure 2.3b the association between drought conditions and degradation. The spatial pattern of the water deficit anomaly indicator in 2010 and 2015-2016 was different from each other. While the drought in 2010 was concentrated in southern Amazonia, in 2015, it mostly affected the north and east portions. Most of the degradation occurred in dryer areas in both years, following the water deficit anomaly indicator spatial distribution.

The results also point out that drought conditions are not the only factor explaining the spatial distribution of total degraded area in a particular year, as the multi-temporal analysis in Figure 2.3c illustrates. The percentage of degraded area overlapping drought conditions areas varies from 1% (2008) to 87.5% (2016) over the period, with marked differences between extreme drought and no-extreme drought years. In years with high values of degraded areas but normal precipitation, such as 2017 (22,361 Km²) and 2018 (23,373 Km²), this relation does not exceed 32%. Furthermore, from August 2009 to July 2010, for example, we observed the prevalence of degradation in areas with wet conditions (59.1%), which may be caused by human-induced factors.

Figure 2.3 - Degradation area by water deficit anomaly indicator. a) Degradation from August 2010 to July 2011 x MCWD anomaly 2010 b) Degradation from August 2015 to July 20016 x MCWD anomaly 2015 c) Graph of degradation area by MCWD anomaly.

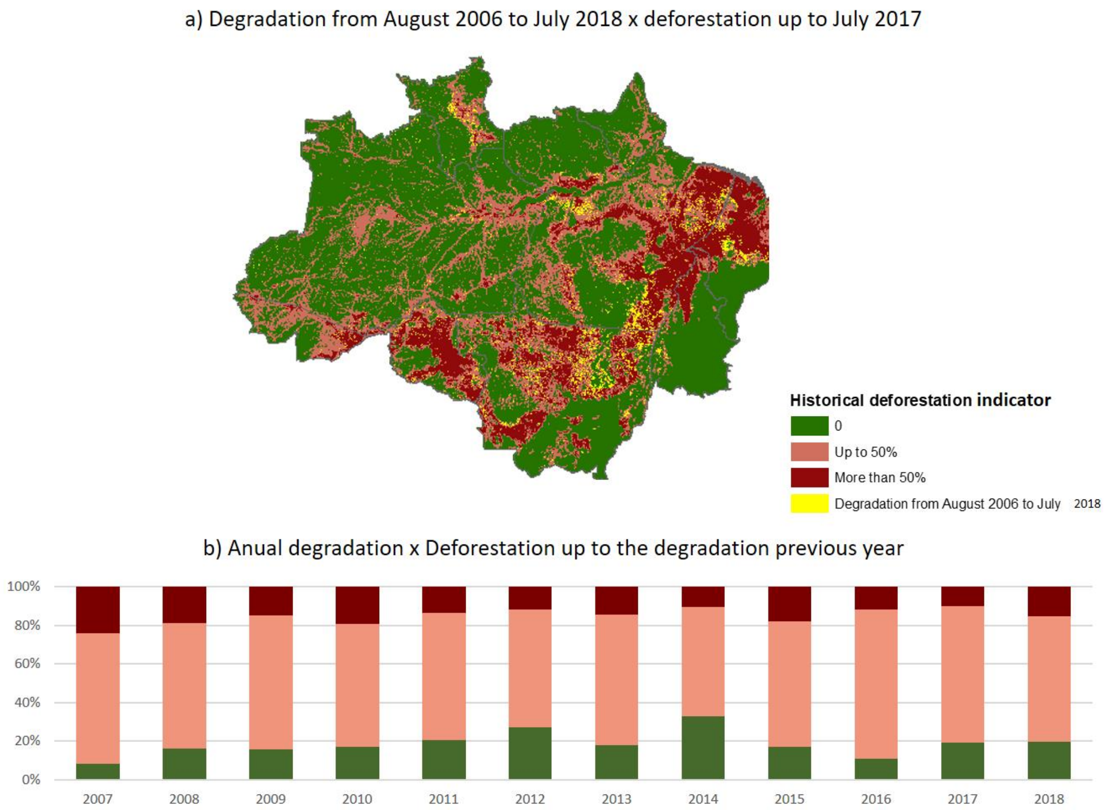


Source: Prepared by the author.

2.3.2 Degradation and historical clear cut deforestation

Our results also point out a strong influence of historical deforestation spatial distribution on degradation occurrence. Our results (Figure 2.4b) show that, on average, only 18% of the areas that suffered forest degradation from 2007 to 2018 had Historical Clear Cut Deforestation Indicator values equal to zero. On the other hand, on average, 67% of the degraded area occurred in areas with Historical Clear Cut Deforestation Indicator values up to 50% and 15% more than 50%. This relation was also expressive in years with extreme droughts events. From August 2010 to July 2011, 66% of the degradation occurred in areas with Historical Clear Cut Deforestation Indicator values up to 50% and 13.6% more than 50%. From August 2015 to July 20016 were 77% and 11.7%, respectively. The map in Figure 2.4a illustrates the accumulated degradation over the entire analysis period (yellow) and the Historical Clear Cut Deforestation Indicator in 2018.

Figure 2.4 - Degradation x Historical Clear Cut Deforestation Indicator a) Map of Degradation from August 2006 to July 2018 x clear cut deforestation up to July 2018. b) Graph of annual degradation versus clear cut deforestation up the previous year.



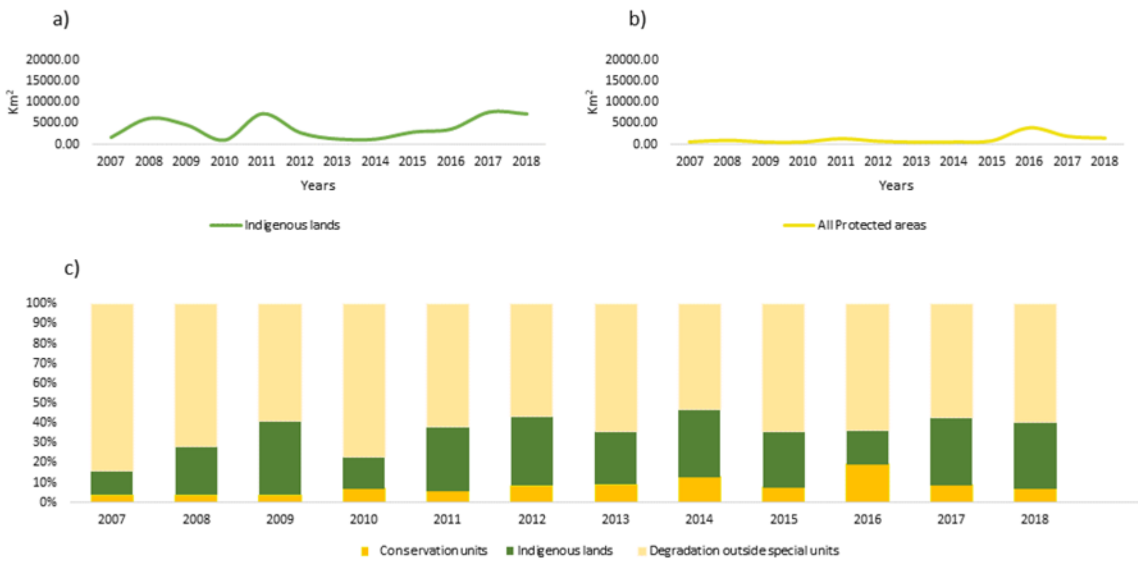
Source: Prepared by the author.

2.3.3 Degradation and protected areas

Our results pointed out that, on average, 58 % of forest degradation during the whole analysis period in the Brazilian Amazon is outside protected areas, keeping in mind that protected areas correspond to 52% of the Brazilian Legal Amazon. Our analysis (Figure

5e) also showed that, on average, 25% of the degradation occurred in Indigenous Territories from 2007 to 2018 period. The Conservation Units, in turn, had the lowest relationship with degradation (7%).

Figure 2.5 - a) Degradation in Indigenous Territories, b) Degradation in Conservation Units c) Proportion degradation by protected areas type.



Source: Prepared by the author.

Along the analysis period, the proportion of degraded areas varied from 3% to 11% in Conservation Units (b). From August 2015 to July 2016, we observed a peak occurrence of forest degradation inside Conservation Units. These areas correspond to 14.6% of the total degraded area in the year. A major part of this amount (98.3%) were inside areas under drought conditions.

Indigenous Territories (c) showed similar behavior to areas outside protected areas (a), with peaks from August 2007 to July 2008, from August 2010 to July 2011 and from August 2016 to July 2018 remaining high until the end of the analysis period. From August 2010 to July 2011, during an extreme drought event, 97.7% of this degradation area took place inside drought condition areas. The proportion of degradation that occurred inside Indigenous Territories over the entire period varied from 11% to 34.5%.

2.4 Discussion

2.4.1 Degradation and water deficit anomaly

Although droughts are part of the natural variability of the climate in the Amazon rainforest, extreme drought events such as those of 2005, 2010 and 2015-2016 were not as frequent, and they are associated with the occurrence of wildfires (MARLON et al., 2009; NOBRE et al., 2016). These extreme droughts can make the forest more flammable either directly by reducing air moisture and increasing fuel or indirectly by decreasing soil moisture, triggering leaf shedding, branch loss, and tree mortality (LONGO, 2014). Even if the Amazon forest rarely burn without an anthropogenic ignition source (COCHRANE, BARBER, 2009), increased flammability makes the forest more vulnerable to degradation, mainly due to forest fires.

Several works discuss the linkages between the degradation and areas which suffered from extreme droughts (ALENCAR et al., 2015; ANDERSON et al., 2015; ARAGÃO et al., 2018; BRANDO et al., 2020). Our results agree with these previous studies and show that in dryer years, the spatial relation between degradation and drought condition areas exceed 87.5%. This relation is particularly relevant when considering the projections of frequency and intensity increase of extreme events (IPCC, 2013). However, Alencar et al. (2011) argue that in a warmer climate, even many consecutive moderated dry seasons can increase the forest susceptibility to fire.

On the other hand, our results over the entire period indicate a weak linkage between degraded areas and drought conditions in years with normal precipitation. For example, although in 2017 and 2018 had been observed elevated degradation levels, the connection between the degraded area and drought conditions does not exceed 32% in these years. While the climate anomalies can be identified as a driving force to degradation (ALENCAR et al., 2011), extreme droughts are not enough to explain the degradation in a particular year (MARLON et al., 2009).

2.4.2 Degradation and historical deforestation

The fragmentation caused by clear cut deforestation exposes the forest along the edges, enhancing its flammability and favoring the increase of wind speeds, insolation rates, and fuel loads (COCHRANE; BARBER, 2009; ALENCAR et al., 2015). For this reason, more edges also mean more exposition to forest degradation caused by fire. Even fires usually occur up to one kilometer from forest edges, there are also fires within the forests, far from the edges (SILVA JUNIOR et al., 2018; COCHRANE, 2001).

Our results pointed out that, on average, only 18% of the degradation took place in areas without historical clear cut deforestation along with its 5x5 neighborhood cells. The use of the clear cut deforested area can also increase the exposure of the remaining forest to fires. Agriculture is a notable example where the fire frequently used in land management can result in its accidentally spread beyond the cultivation, advancing towards the intact forest areas (HOUGHTON, 2012; NOBRE et al., 2016, BARLOW et al., 2020).

According to Aragão et al. (2008), even if land use changes are decisive to determine patterns of fire occurrence, extreme droughts can increase the number of fires in the Amazon even with decreased clear cut deforestation rates. Moreover, Aragão et al. (2018) pointed out the decoupling between degradation and clear cut deforestation during the 2015-2016 extreme drought. Our analysis considered the period from 2007 to 2018 and extended our study to the surroundings, along with 5x5 neighborhood cells. The results showed a strong linkage between degradation and historical clear cut deforestation. This correspondence reaches more than 80% in all years (except from August 2011 to July 2012 and from August 2013 to July 2014). It can indicate the influence of clear cut deforestation in both the spatial pattern and the amount of degradation. On the other hand, on average, only 8% of the degraded area was converted to clear cut deforestation (ASSIS et al., 2020), indicating that, although the historical clear cut deforestation influences the degradation occurrence, most of the degradation is not the starting point for clear cut deforestation.

2.4.3 Degradation and protected areas

Conservation Units play a central role in forest preservation, and their expansion (VERÍSSIMO; COCHRANE; SOUZA, 2002) is seen as fundamental to limit the spread of degradation since it is assumed that forests within these areas are less susceptible to degradation (COCHRANE; BARBER, 2009). Indigenous Territories preserve the rights of Indigenous Peoples foreseen in the 1988 Federal Constitution and are also crucial for the environmental preservation of the Amazon. Walker et al. (2020) warn that even though Conservation Units and Indigenous Territories are more effective than other areas in preserving forest vegetation, they are not impervious. They showed that in the entire Amazon basin between 2003 and 2016, twice as much biomass was lost outside Indigenous Territories and Conservation Units than inside of them. According to Nepstad et al. (2006), Indigenous Territories proved to be as or more effective than Conservation Units in preventing clear cut deforestation and fire. Our studies show that, on average, 25% of the degradation that occurred in the Brazilian Amazon was located inside Indigenous Territories. In comparison, 7% occurred inside Conservation Units; reinforcing Conservation Units have proven to be one of the most important tools for forest conservation (SOARES-FILHO; RAJÃO, 2018). Our results differ from Nepstad et al. (2006) probably due to i) methodology: They used deforestation data from 1997 to 2000 and fire data from GOES satellite for 1998, considering Conservation Units larger than 10.000 ha, and ii) Amazon human occupation dynamics: during the last 20 years, more Conservation Units and Indigenous Territories were created, and the land use and cover dynamics in Amazon have changed.

Disturbances linked to climate change and extremes can have effects that go beyond administrative limits if the responsible institutions are not prepared to respond to threats (WALKER et al., 2020). When analyzing the evolution of degradation in each type of protected area over the years, we observed peaks over years of extreme droughts in Indigenous Territories from August 2010 to July 2011 and in Conservation Units from August 2015 to July 2016. In both cases, most of the degradation in these units occurred in drought condition areas. These results show that even though Indigenous Territories and Conservation Units play an essential role in the environmental preservation of the region, they are exposed to extreme drought pressure. Brando et al. (2020) advise of the fact that large extensions of primary forests, under severe drought conditions, may be more susceptible to burning because they provide high fuel continuity due to forest connectivity.

The analyzes also show that degradation in Indigenous Territories initiates an upward trend that begins in 2015 and remains until the end of the analysis period. While economic exploitation in indigenous territories is prohibited, they are under increasing pressure, which can compromise both the maintenance of biodiversity and compliance with assumed climate agreements (LIMA et al., 2020). This pressure has increased with government demonstrations that aim to integrate indigenous people into the national economy and create obstacles to the demarcation processes of new Indigenous Territories (BEGOTTI; PERES, 2019).

2.5 Conclusion

This work made it possible to build an extensive degradation time series and to understand how it relates to the indicators analyzed over the years. Our results indicated a weak link between degradation and drought condition areas over the entire period (from August 2006 to July 2018), although, in extreme drought years, the spatial relationship exceeds 92%. The connection between degradation and historical clear cut deforestation remained high (more than 65%) during the entire period.

We also show that, on average, 25% of the degradation occurred inside Indigenous Territories and 9% in Conservation Units. These results indicate that even though Indigenous Territories and Conservation Units play an essential role in the environmental preservation of the region, they are not impervious to forest degradation, especially for Indigenous Territories, which initiates an upward trend that begins in 2015-2016 and remains until the end of the analysis period.

Even though other variables should be considered in future works, this study analyzed several relationships between degradation, climate anomalies, public territory control and human occupation over time, contributing to a better understanding of forest degradation dynamics in Brazilian Amazon.

3 CO_2 EMISSIONS FROM FOREST DEGRADATION IN BRAZILIAN AMAZONIA[1]

3.1 Introduction

Forest degradation carbon emissions are still poorly quantified, although climate change mitigation schemes, such as the UN-led Reducing Emissions from Deforestation and Forest Degradation (REDD+), will require accurate estimates of carbon emissions following forest disturbance (OLANDER et al., 2008; ARAGÃO et al., 2014; RAPPAPORT et al., 2018; MAXWELL et al., 2019). In general terms, forest degradation is a reduction in the capacity of a forest to produce ecosystem services such as carbon storage and wood products as a result of anthropogenic and environmental changes (THOMPSON et al., 2013). It is a process with a broad distribution in the global forests and is one of the major causes of biodiversity loss (IPBES, 2019), due to multiple factors such as unsustainable logging, fire, agriculture, invasive species, firewood gathering, and livestock grazing. In this Chapter, we limit the analysis of forest degradation to the occurrence of forest fires and disordered selective logging activities and assess the possible impacts on annual emissions of greenhouse gases.

In the Brazilian Amazon, forest degradation is mostly associated with logging and fire, or a combination of both (NEPSTAD et al., 1999; FEARNSIDE, 2005). In the last years, forest degradation has shown significant values, frequently higher than deforestation (INPE, 2020; INPE, 2020b). In dryer years, such as 2010 and 2015, the total degradation area reached over 2,000,000 ha (Figure 3.1). The processes leading to degradation impact biodiversity (BARLOW; PERES, 2008; BERENGUER et al., 2018), carbon stocks (GERWING, 2002; FOLEY et al., 2007; BLANC et al., 2009; ANDERSON et al., 2015; LENNOX et al., 2018; SILVA et al., 2018) and increase forest vulnerability to future burning (NEPSTAD et al., 1999).

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[1] This chapter is an adapted version of the paper:

ASSIS, T. O.; DE AGUIAR, A. P. D.; VON RANDOW, C.; DE PAULA GOMES, D. M.; KURY, J. N.; OMETTO, J.; NOBRE, C. A. CO2 emissions from forest degradation in Brazilian Amazonia. **Environmental Research Letters**, v. 15, n. 104035, jun. 2020.

According to Rappaport et al. (2018), the type of degradation, its frequency, timing, and severity influence changes in the biomass. Therefore, to quantify the carbon emissions derived from forest degradation, it is important to depict its pathways. This knowledge allows us to assess the impact of the different patterns of land cover changes in carbon accounting systems. Santos et al. (2001) mapped and followed the evolution of polygons of logging between 1988 and 1998, leading to clear cutting or forest regeneration, using remote sensing techniques. Of the total area of 17,146 Km^2, mapped in the Brazilian Amazon, 15.6% were converted into clear-cut deforestation, 43.5% were characterized as degraded forest, and 40.9% regenerated the vegetation cover. Kury (2016) performed a similar analysis, tracing trajectories from degradation started in 2007. The results pointed out that, of the areas designated as degraded in 2007, 21% were converted into clear-cut by 2012, and 31% followed a trajectory of more degradation events. In the remaining area (48% of the area), no new degradation events or clear-cut occurred.

In this Chapter, we trace degradation trajectories in the Brazilian Amazon from August 2006 to July 2016 to analyze the degradation dynamics, based on Santos et al. (2001) and Kury (2016). Then, we adapted the degradation component of the spatially-explicit INPE-EM carbon emission model (AGUIAR et al., 2016) to represent biomass changes following degradation events and assess their impact on the carbon balance.

3.2 Methods

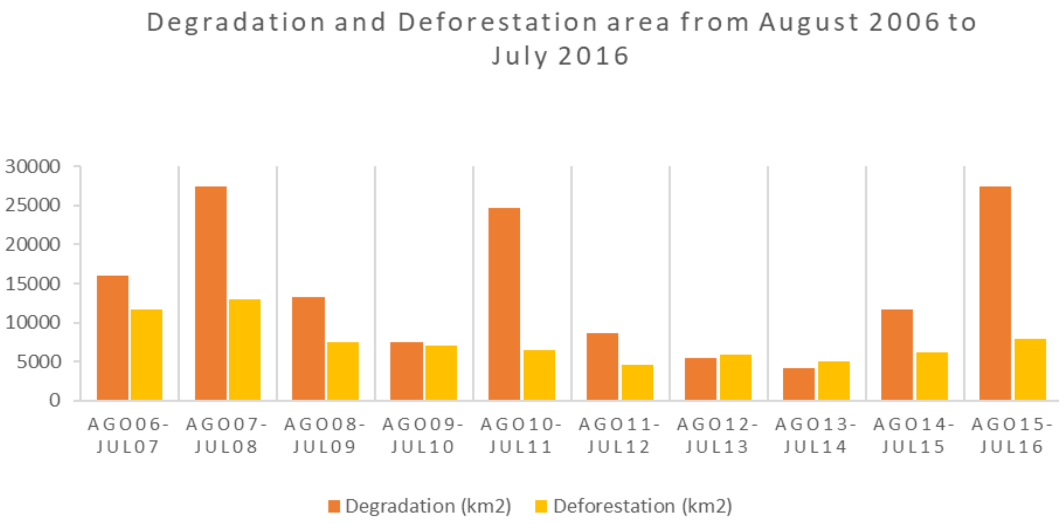
3.2.1 Degradation and clear-cut data

We used the DEGRAD system (INPE, 2020) as our source of old-growth forest degradation information. DEGRAD is an operational system that identifies old-growth forest areas exposed to forest fires and disordered selective logging. The system is a complement to the PRODES system (INPE, 2020a), also developed by that identifies the total removal of vegetation (clear-cut deforestation) in old-growth forest areas.

The mapping of the degraded areas is performed each year independently, without removing areas identified as degraded in the previous years from the analysis. Thus, the DEGRAD system allows assessment of areas that are in the process of regeneration after the degradation event. Therefore, we can consider the information provided by the DEGRAD system in a given year as the indicator of an on-going degradation process caused mostly by fire or logging activities, although some natural disturbance events cannot be differentiated from anthropogenic ones by the DEGRAD product.

PRODES and DEGRAD systems generate annual products based on Remote Sensing images acquired from August of the previous year to July. Therefore, our analysis and estimates of emissions in 2007, for example, refer to the period from August 2006 to July 2007 as they are inferred using PRODES/DEGRAD products. Our analysis covers the period from August 2006 to July 2016. Figure 3.1 presents the annual forest degradation and deforestation rates as estimated by the two systems. In terms of extension, the PRODES and DEGRAD system only monitors old-growth forests. Once an area is clear-cut, it is not monitored in the following years, even when these areas are eventually abandoned, giving way to secondary forests. Future land cover changes in these areas are monitored by a third INPE system, called TerraClass (INPE, 2020c).

Figure 3.1 - Forest degradation (orange) and clear cut deforestation (yellow) annual rates as estimated by the PRODES and DEGRAD Monitoring Systems.



Source: Prepared by the author.

3.2.2 Degradation trajectories

The trajectories are built by analyzing the fate of all polygons identified by DEGRAD in a given year (the trajectory initial reference year). We intersect them with the DEGRAD and PRODES polygons in the following years, looking for overlaps. As a result, we identified three degradation trajectories

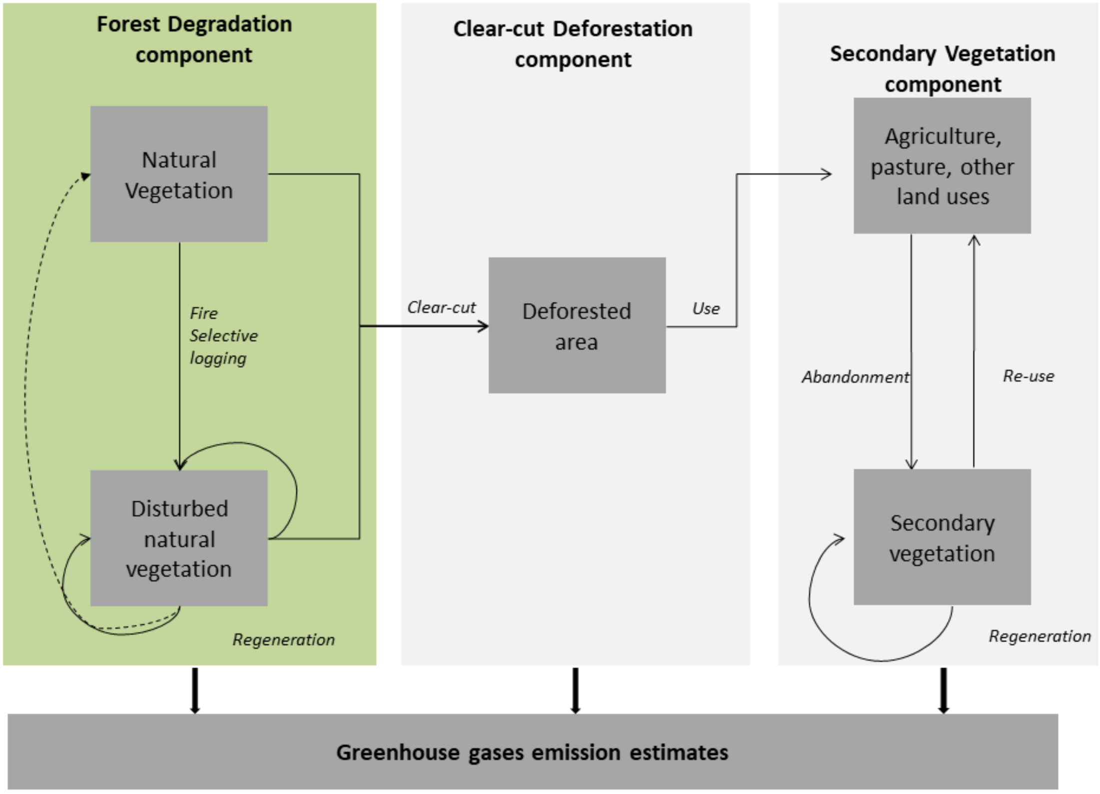
- Degradation to Clear Cut Trajectory: areas identified by the DEGRAD system in a reference year (e.g., 2007) that ended-up being fully cleared and converted (i.e., as detected by PRODES) in any of the following years.
- Multiple Degradation Events Trajectory: areas under recurrent degradation (detected by DEGRAD at least in two distinct years), but that was not fully cleared during the analyzed period.
- Single Degradation Event Trajectory: degradation polygons identified in the reference year that did not intersect with any other degradation or clear-cut polygons in subsequent years.

Polygons identified as part of the trajectory were not considered for the following reference years to avoid double-counting. For example, a polygon observed by DEGRAD 2007 and DEGRAD 2008 is considered part of the 2007 Multiple Degradation Events Trajectory and discarded from the 2008 trajectory analysis.

3.2.3 INPE-EM modeling approach

We used the INPE-EM carbon emission model to estimate the CO_2 balance for the Amazon region until 2016, considering the clear-cut deforestation and forest degradation processes. INPE-EM (AGUIAR et al., 2012, 2016) combines spatially explicit maps of biomass and land cover changes in three distinct components: a) clear-cut deforestation, b) secondary vegetation, and c) forest degradation, to represent emission processes in an integrated way. INPE-EM is based on the bookkeeping model proposed by Houghton et al. (2000) and aims to generate annual estimates of emissions of greenhouse gases (GHG) by the land cover change in a spatially explicit way. This model estimates 1st order emissions that assume that all emissions occur at the time of the land cover change and 2nd order emissions, used in this Chapter, which represent the gradual process of liberation and carbon absorption as occurs in fact. These 2nd order emissions estimates have an attenuated response about land cover changes and carry the influence of lagged emissions due to historical processes that occurred in previous years.

Figure 3.2 - INPE-EM model diagram.



Source: Prepared by the author.

INPE-EM Vegetation Removal Component calculates 1st order and 2nd order emissions due to clear cut deforestation. The second-order estimate represents the carbon release rate into the atmosphere over time (Figure 3.2), considering that part of the biomass is converted into wood products, a part is burned, and part is left on the ground, suffering gradual decomposition (above or below ground). In addition to gross emissions derived from clear cut deforestation of pristine areas, INPE-EM calculates net emissions that combines the dynamics of secondary vegetation in deforested areas. The secondary vegetation component works independently, estimating the dynamics not in the old-growth forest areas, but only in deforested areas, considering the abandonment cycle (regrow and cut) of the secondary vegetation. We used Terraclass land use and cover data (INPE, 2020c) to estimate the secondary vegetation growth in the model.

Additionally, the biomass stock can increase or decrease according to degradation events. The INPE-EM degradation component, introduced by Aguiar et al., (2016), calculates CO_2 emission and absorption, dynamically altering the biomass of the old-growth forest areas as the result of degradation events and post-event regeneration. Thereby, it captures both the short-term (carbon release and uptake) and long-term effects (changes in carbon stock due to forest regeneration after the disturbance) of the degradation process. After computing the total amount of lost biomass and consequent CO_2 emission in a given year, the model allows for the regeneration of the aboveground live biomass (AGB), assuming the original value will be reestablished after a given number of years, with a constant growth rate, in the original version of the model. The CO_2 absorption is calculated considering this growth rate and the forest area remaining in each spatial aggregation unit (cell).

We modified the original version of the INPE-EM degradation component to improve the representation of the biomass changes following a degradation event. We adapted this component to permit the use of different growth curves to represent the regeneration of the AGB and allow the use of multiple AGB loss factors in the same model. This modification allowed us to describe how distinct elements influence the changes in biomass during degradation events, such as its recurrence.

3.2.4 INPE-EM parametrization

The model was run from 1960 to 2016 to take into account historical emissions of land cover change in Amazonia. A relatively long-time interval is necessary to represent the gradual process of carbon liberation and absorption throughout the years. Thereby, present emissions carry the influences of historical land-use processes, and contemporary processes will influence future carbon emissions.

We used 50 x 50 ha cells to represent the spatial variables in the model. In this Chapter, we used INPE-EM non-spatial mode from 1960 to 2006 and spatial mode from 2007 to 2016. Spatial data is available from 2007 to 2016. To account for lagged emissions and historical disturbances in the biomass, we used historical non-spatial data, based on the literature (Table 3.1) for the 1960 to 2006 period, following the approach adopted in Aguiar et al. (2012). In the INPE-EM model, the non-spatial models equivalent to using a single cell for the entire area, which is added to the results of the spatial mode (AGUIAR et al., 2012). If, on the one hand, this adds uncertainties related to the absence of spatial data for the historical period, on the other hand, this procedure allows us to estimate the impact of emissions from past processes on current emissions. Table 3.1 describes the parameter settings for the INPE-EM degradation component.

Table 3.1 - Parameters settings for the INPE-EM degradation component.

Parameter	Description	Non-spatial	Spatial
Biomass	Average biomass in a cell unit	233 $MtCO_2$ ha^{-1}	Brazilian Third National GHG Inventory (MCTIC, 2016)
Degradation	Percentage of cell unit identified as degraded that year by fire/logging events	155,872 ha (Santos et al. 2001)	DEGRAD (INPE, 2020)
AGB loss	Percentage of AGB lost as a result of the event	54,2% (Rappaport et al. 2018)	54,2% and 83% (Rappaport et al. 2018)
BGB loss	Percentage of BGB lost as result of the event	0	0
Deadwood loss	Percentage of deadwood lost as a result of the event	0 (Berenguer et al. 2014)	0 (Berenguer et al. 2014)
Litter loss	Percentage of litter lost as result of the event	0 (Berenguer et al. 2014)	0 (Berenguer et al. 2014)
Growth curves	Rates of regeneration of the AGB along the years	Based on (Rappaport et al. 2018) relationship between intact and 1x burned forests	Based on (Rappaport et al. 2018) relationship between a) intact and 1x burned forests, b) intact and 2x burned forests

We adopted the biomass spatial data from the Brazilian Third National GHG Inventory (MCTIC, 2016). The average AGB used for the historical period before the availability of spatial data was 233 Mt CO_2 ha^{-1}, corresponding to the average of AGB in the degraded areas for the spatial period considered, according to the National Inventory of GHG emissions (MCTIC, 2016). We used the DEGRAD System to provide degradation data for the INPE-EM spatial mode. For the non-spatial mode, we used the results of Santos et al. (2001), who assessed an area of 1,714,600 ha degraded forests in the Brazilian Amazon between 1988 and 1998. We considered homogeneous annual average value (155,872 ha) for the period from 1988 to 2006. No degradation was considered before this period (1960-1987), following Aguiar et al. (2016).

We used the relationship between intact and degraded forests over the years described by Rappaport et al. (2018) to represent the biomass loss and recovery in a degraded area. Their results presented the biomass changes following conventional logging and fire pathways. We adopted the "1 time burned (average)" for the historic period. For the spatial mode, we combined "1 time burned (average)" e "2 times burned" relations. We based on it to define the AGB loss and generate the AGB regeneration curves.

Since the degradation polygons are frequently smaller than spatial model resolution, the information about the recurrence of degradation in a cell is not enough to decide which relations between intact and degraded forests to use. To improve this relation, we combined this information with the results of the trajectories analysis, presented in Section 3.2.2. If the cells showed degradation recurrence and more than 50% of its degradation fits on the Multiple Degradation Events Trajectory, the model adopted "2 times burned" relations (RAPPAPORT et al., 2018) to define AGB loss and AGB regeneration curves for this cell. Otherwise, the model uses the "1 time burned (average)". The other model parameters were based on Aguiar et al. (2016).

3.3 Results

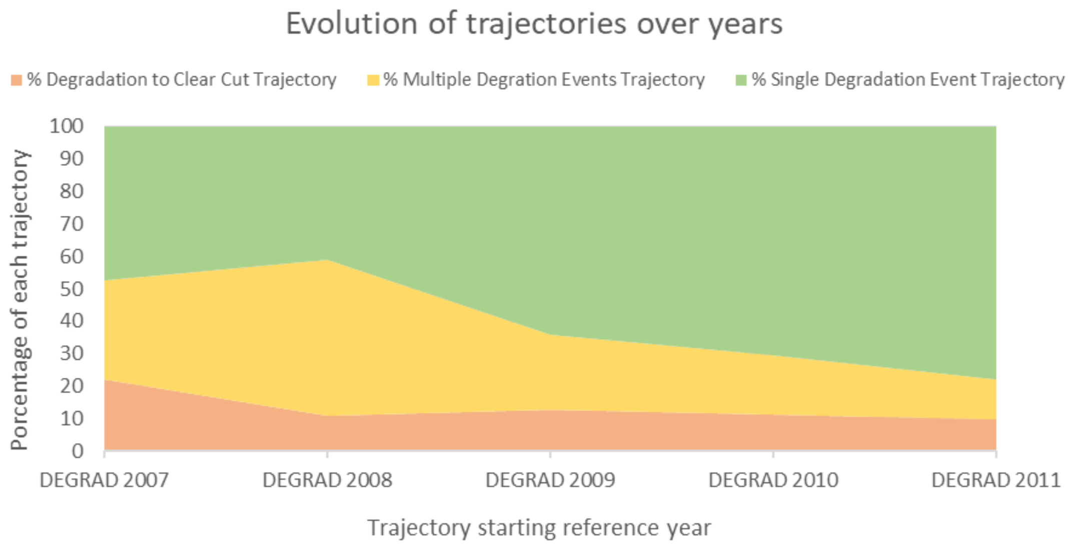
3.3.1 Trajectories distribution

The trajectory analysis shows that the Single Degradation Event Trajectory is prevalent in the Amazon, during all the analyzed period covering 61% of the total degraded areas in a regeneration path without subsequent disturbances in the following ten years. Although in this section, we focus on trajectories starting from DEGRAD 2007 (August

2006 – July 2007) to DEGRAD 2011 (August 2010 – July 2011) we observed this trend throughout the other years.

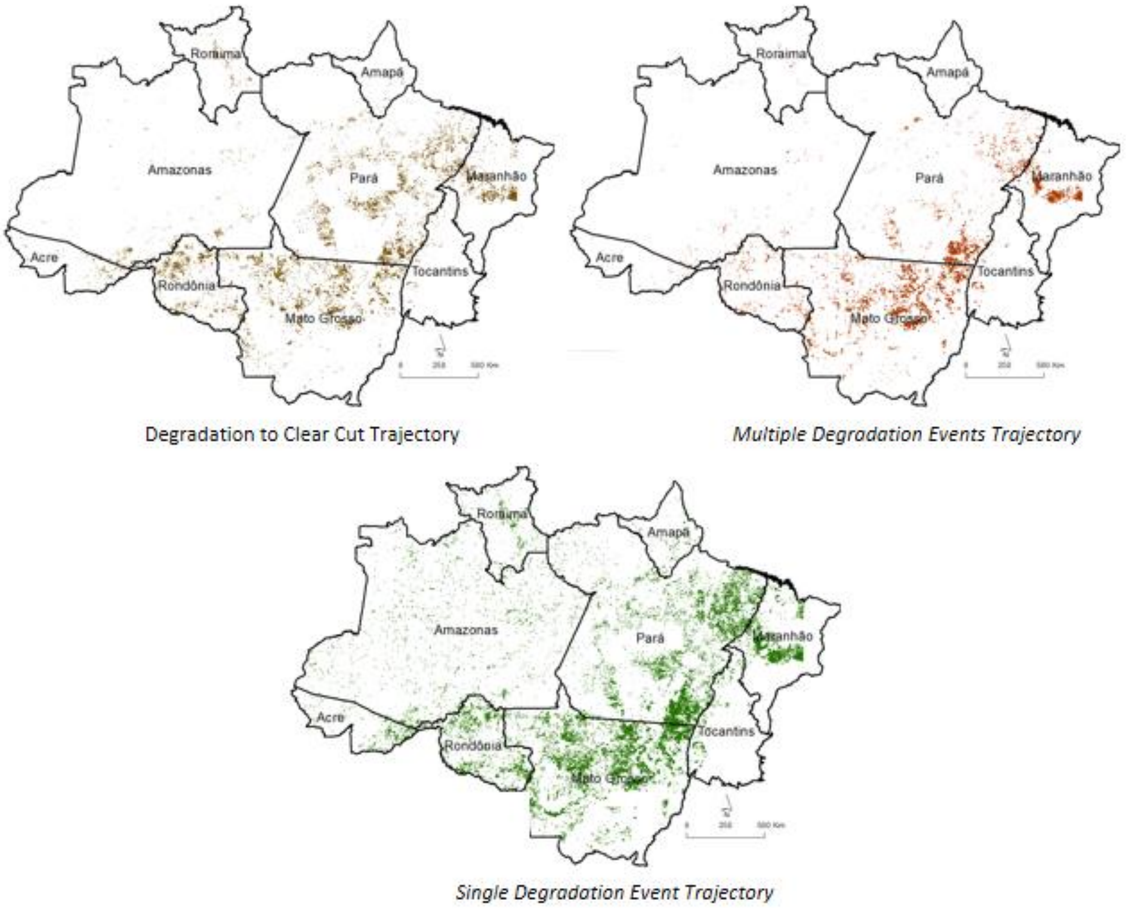
Analysis of the evolution of trajectories shows a substantial increase in the Single Degradation Event Trajectory since DEGRAD 2010, reaching more than 70% of the total (Figure 3.3). Contrastingly, our analysis also shows that 13% are on the Degradation to Clear Cut Trajectory - a tendency observed since DEGRAD 2008. The other 26.5% of areas are part of the Multiple Degradation Events Trajectory, with recurring events of fire or logging.

Figure 3.3 - Temporal distribution of Degradation to Clear Cut Trajectory (Orange), Single Degradation Event Trajectory (Green), and Multiple Degradation Events Trajectory (Yellow).



Source: Prepared by the author.

Figure 3.4 - Spatial distribution of the three trajectories of this study for the period of August 2006 to July 2016.



Source: Prepared by the author.

Figure 3.4 illustrates the heterogeneous spatial distribution of the three trajectories. The Single Degradation Event Trajectory was found all over the Amazon, widely scattered in remote areas, although more concentrated closer to previously opened areas and to the new deforestation frontiers. The Multiple Degradation Events Trajectory was found in areas with high levels of historical deforestation, mainly in Mato Grosso and the Tocantins States. Degradation to Clear Cut Trajectory appears close to previously opened deforested areas, expanding towards the Central Amazon from the south.

3.3.2 CO_2 emission estimates

The INPE-EM model allowed us to estimate the carbon balance in an integrated way and to assess the impact of the degradation process on it. Within the entire model period, CO_2 net emissions totaled 34.943 Gt CO_2, considering the emissions from forest degradation and deforestation, absorption from degraded forest recovery, and secondary vegetation growth and emission from the cut of secondary vegetation. The results show an increase in the contribution of forest degradation to net emissions. While degradation (emission and absorption presented in Table 3.2) corresponds to 1.3% from 21.9 Gt CO_2 net emissions from 1981 to 2006, it corresponds to 16.2% from 5.4 Gt CO_2 emitted from 2007 to 2016.

Our results indicate the increasing importance of degradation in CO_2 gross emissions. Forest degradation emissions add up to 0.8 Gt CO_2 from 1981 to 2006, while between 2007 and 2016, they were 2.7 Gt CO_2. Of the total of 24.9 Gt CO_2 of gross emissions from 1981 to 2006, the degradation corresponds to 3.2%, whereas clear cut deforestation shares to 91.7% (22.9 Gt CO_2). However, degradation is responsible for 30.4% of the 8.9 Gt CO_2 gross emissions between 2007 and 2016. In the same period, clear cut deforestation share decreased to 57.4% (5.1 Gt CO_2).

The aggregate effects of the post-disturbance regeneration partially offset these emissions. The CO_2 absorption due to degraded forest recovery from 1981-2006 was 0.5 Gt CO_2, which amount to 64.9% of the 0.8 Gt CO_2 emitted due degradation in the same period. This proportion is 67.6% when we consider the period from 2007 to 2015 (2.7 Gt CO_2 emitted due to forest degradation and 1.8 Gt CO_2 absorbed due to degraded forest recovery).

Table 3.2 shows the estimates of CO_2 emissions divided into three periods: a) from 1960 to 1980, b) from 1981 to 2006, and c) from 2007 to 2016. Although all the period before 2007 considered historical non-spatial data, 1981-2006 included forest degradation process, while the 1960-1980 period only estimated emissions from clear cut deforestation. We emphasize that, as we used PRODES and DEGRAD as our spatial deforestation and degradation source data, 2007, for example, refers to the period from August 2006 to July 2007.

Table 3.2 - Carbon Balance for the Brazilian Amazon from 2007 to 2016 (lagged processes since 1960 due to degraded areas regeneration and secondary vegetation regrowth in clear cut areas).

Year	**CO_2 Emissions (Mt CO_2)**			**CO_2 Absorption (Mt CO_2)**		**Gross Emission (Mt CO_2)**	**CO_2 Balance (Mt CO_2)**
	Deforestation	**Secondary vegetation cut**	**Degradation**	**Secondary vegetation growth**	**Degraded forest recovery**		
2007	807	89	317	-156	-32	1213	1026
2008	748	93	499	-161	-214	1340	965
2009	633	98	190	-164	-230	921	527
2010	555	103	157	-166	-196	815	454
2011	492	107	395	-168	-182	994	644
2012	413	110	159	-169	-233	682	280
2013	381	114	97	-170	-215	592	206
2014	348	119	78	-172	-183	545	191
2015	343	123	180	-173	-165	646	308
2016	369	127	622	-174	-172	1118	771
Total 2007 - 2016	5089	1083	2694	-1673	-1822	8866	5372
Total 1981 -2006	22851	1265	806	-2484	-523	24922	21910
Total 1960 -1980	7952	84	0	-371	0	8036	7661

3.4 Discussion

The INPE-EM model allowed us to estimate the net carbon balance in an integrated way and assess the impact of the degradation process on it. We link the analyses of the three trajectories of forest degradation in the Brazilian Amazon to the INPE-EM results, discussing the results in the context of previous studies.

3.4.1 Trajectories of forest degradation

The increasing dominance of the Single Degradation Event Trajectory points to the significance of isolated degradation events spread all over the Amazon (Figure 3.4). While this trajectory represents 47.5% of the fate of degraded areas identified by DEGRAD 2007, very similar to the results pointed out by Kury (2016), its share increased in the following reference starting years. For example, for the degraded areas identified by DEGRAD 2010, 70.6% belonged to this category. The spatial pattern of Single Degradation Event Trajectory (Figure 3.3) possibly indicates that those events are not merely linked to anthropic factors. Although this degradation can also indicate non-anthropic disturbances, it requires more investigation to pinpoint how much of that might be due to natural phenomena such as climate events, which cause forest blowdowns (NEGRÓN-JUÁREZ et al., 2018). Aragão et al. (2018) highlighted the influence of severe droughts in the increase of Amazon forest fires, although our results show the prevalence of Single Degradation Event Trajectory even in non-drought years.

At the same time, our trajectory results also show a slight decrease in the share of the Clear-cut trajectory. While for degraded areas identified in DEGRAD 2007 represented 22 % of their fate, after DEGRAD 2008, its share stabilized around 11%. This trajectory shows a concentrated spatial pattern close to previously deforested areas, indicating the initial stages of the clear-cut deforestation process (PINHEIRO, 2015). Two interlinked factors may explain the decrease in the temporal share of this trajectory. First, the sharp decrease in deforestation rates from 2006 to 2014 is not observed in the temporal evolution of forest degradation rates (Figure 3.1). Second, the increase of scattered degradation events discussed above. This decoupling of deforestation and forest fires events have been reported in the literature before (ARAGÃO et al., 2018).

The trajectory of repeated degradation events within a ten-year period, Multiple Degradation Events Trajectory, was found in areas with high levels of historical deforestation, mainly in Mato Grosso and the Tocantins States. These areas represent the most degraded and vulnerable forests.

3.4.2 How these different trajectories impact net CO_2 emissions?

The decoupling between deforestation and forest fires observed in the trajectory analysis can also be seen in the CO_2 emissions estimated in the INPE-EM model. Our results indicate that forest degradation contribution to the gross emissions increased from 3.2% (from 1981 to 2006) to 30.3% (from 2007 to 2016). On the other hand, deforestation's contribution decreased from 91.7% to 57.4%. The decrease in Brazilian Amazon deforestation rates since 2004 contributed to this situation (Figure 3.1). Although our results show expressive degradation emissions in the carbon balance, its values presented lower values than deforestation emissions even in dryer years, which agrees with the results obtained by Aguiar et al. (2016) and Aragão et al. (2014). However, there is enormous uncertainty about the future of these processes. Evidence of an increase of droughts due to climate change (MARENGO et al., 2018), associated with the recent rise of clear-cut deforestation rates (INPE, 2020a), pose considerable threats to the region, with potential feedback on the global climate.

The prevalence of the Single Degradation Event Trajectory highlights the importance of considering the absorption by degraded forest recovery in the carbon balance in the Brazilian Amazon. Although the prevalence of this trajectory can have positive effects on the carbon balance compared to the other trajectories, degradation events drastically affect biodiversity (IPBES, 2019). These events may drive long term consequences altering forest structure and composition, leading to the impoverishment of forests and further increase flammability for several years (BARLOW; PERES, 2008). The pulverized pattern observed in the Single Degradation Event Trajectory contributes to more areas throughout the Amazon being exposed to these forest degradation impacts.

3.4.3 Carbon balance in relation to previous studies

Studies estimating carbon emissions from multiple land cover change processes are becoming more common. For example, Tyukavina et al. (2017) pointed out that by 2013, secondary vegetation deforestation, together with old-growth forest degradation, became comparable to clear cut deforestation. Aragão et al. (2018) also pointed to the growing contribution of forest degradation to gross emissions. Their results indicated that gross emissions derived by wildfire correspond to more than 50% of those from forest deforestation during drought years. Our results show proportions varying from 37.2% to 55.6% between degradation and gross emission in dryer years (see Table 3.2). However, we only considered degradation in old-growth forests. On the other hand, both Aragão et al. (2018), Tyukavina et al. (2017) did not consider the absorption due to the regeneration of degraded old-growth forests.

Baccini et al. (2017) estimated net emissions considering forest growth and losses result from deforestation and forest degradation. Their results indicated 324.8 Mt CO_2 year^{-1}. Our results pointed 537 Mt CO_2 year^{-1} in the same period. Two factors can explain this difference. First, Baccini et al. (2017) analyzed only AGB, whereas our model also considers belowground biomass, litter, and deadwood. Second, our model considers the historic process of evolving land change dynamic and some lagged emissions such as wood products, not estimated by Baccini et al. (2017).

Aguiar et al. (2016) also calculated net emissions considering deforestation and forest degradation dynamics, using the INPE-EM model. The positive variation verified in our degradation emission is probably due to the AGB loss factor. We adapted INPE-EM to work with two AGB loss factors to represent the impact of recurrent degradation within a cell in the model. On the other hand, the refinement of regrowth curves to represent the degraded forest regeneration lightly attenuated our degradation absorption estimates in relation to Aguiar et al. (2016).

3.4.4 Uncertainties, limitations, and future research

Although the processes of forest degradation are still poorly understood in the Brazilian Amazon, recent efforts are contributing to advance the understanding through field observation and remote sensing (BERENGUER et al., 2014, 2018; ANDERSON et al., 2015; LONGO et al., 2016; RAPPAPORT et al., 2018; WITHEY et al., 2018). Such efforts are essential better to represent the forest degradation processes in greenhouse gas models. AGB losses due to the degradation are one of the main uncertainties in the model. We used our trajectories analysis to decrease this uncertainty by combining trajectories information with degradation recurrence within a cell to decide which AGB losses and regrowth curves assume in each case.

Another improvement for future work relates to the trajectories definition. We used a 10-years period since we are aware that the longer the interval, the larger the chance of capturing multiple events. However, this should reduce the comparable intervals within each trajectory. Although DEGRAD data is only available from 2007 to 2016, data from other systems could be combined, for example, from the DETER B system (INPE, 2020b).

Despite the uncertainties associated with the fact that there is no spatial data for the historical period, our results show the importance of including the legacy emissions in the analyzes related to the carbon balance.

3.5 Conclusion

The INPE-EM model made possible an integrated analysis of the CO_2 emissions and absorptions from land cover changes over the period. The results obtained for the Brazilian Amazon confirm the potential impact of forest degradation in the regional carbon balance. The total CO_2 emission arising from degradation is smaller than that of deforestation, but it is still expressive.

The decoupling between degraded and deforested areas observed from the low occurrence of the Degradation to Clear Cut Trajectory reinforces the importance of considering CO_2 emissions from degradation since their impacts cannot be calculated from the deforestation CO_2 emissions alone. The CO_2 absorption from degraded forest recovery presented an essential role in the carbon balance. The prevalence of the Single Degradation Event Trajectory can increase this role. Future research could advance on understanding the links between the increase of such events to biophysical, climatic, and anthropogenic factors, as they are spatially decoupled from the clear-cut deforestation process and not restricted to drought years.

4 FUTURE FOREST DEGRADATION AND CO_2 EMISSIONS FOR THE BRAZILIAN AMAZONIA

4.1 Introduction

Land use and cover changes are closely linked to sustainability and are a central factor in the mediation between human and physical systems (TURNER et al., 1995; FOLEY et al., 2005; LAMBIN; MEYFROIDT, 2010; REENBERG; FENGER, 2011). Processes of land use and cover changes are transformations in the land surface associated with the use made of its natural cover, such as deforestation, forest degradation, urbanization (GEIST; LAMBIN, 2006). Nevertheless, not all of these changes deal with conversions to new types of land uses or cover. Some processes, such as forest degradation, which consists of the partial forest loss due to anthropic actions or environmental changes, are modifications suffered by the surface that change the current conditions but do not convert it to a whole new land cover class. In the Brazilian Amazon, this process mainly involves a combination of wood logging and fire (NEPSTAD et al., 1999; GERWING, 2002; ASNER et al., 2006; COCHRANE; BARBER, 2009), causing biodiversity loss (IPBES, 2019, Barlow, 2016), changes in forest structure (BARLOW; PERES, 2008) and carbon stocks (BERENGUER et al., 2014; ANDERSON et al., 2015; RAPPAPORT et al., 2018; SILVA et al., 2018) and other consequences.

Land cover changes impact at local and global scales (TURNER et al., 1995; GEIST; LAMBIN, 2006) motivates the analysis of its causes and consequences. This analysis can be supported by models that quantify the relationships between land cover changes and their driver factors. Models help to organize knowledge, understand data relationships, and their possible economic and environmental implications, in addition to enabling the evaluation of public policy options in the current trajectories (PIJANOWSKI et al., 2002). Scenarios are plausible stories about the future. Combined with degradation models, scenarios can help to explore their impact on different socioeconomic and environmental conditions. Fonseca et al. (2018) and Le Page et al. (2017) developed fire probability scenarios for 2100 combining land use changes and climate scenarios RCP4.5 and 8.5.

Models including interactions of land use with climate, biodiversity, hydrological cycle, soil or greenhouse gas emissions are increasingly used to understand and represent human-nature interactions (LEGESSE; VALLET-COULOMB; GASSE, 2003;

DEFRIES; ESHLEMAN, 2004; FEDDEMA, 2005; BETTS et al., 2007; LI et al., 2007; AGUIAR et al., 2012). Regarding CO_2 emissions, several models seek to represent their emissions due to land use changes, using different approaches. The bookkeeping model (Houghton, 2002) represents the carbon flow from the cut of given initial biomass, where part of this biomass is burned, deposited as slash, or stored in products. This model proves to be very useful to explore the impacts of different land use processes, as it allows us to monitor and analyze post-forest disturbance dynamics. INPE-EM presents an improvement of this model, representing it spatially. Some authors developed CO_2 emissions scenarios due to degradation in the Brazilian Amazon. Faria et al. (2018) explored the effects of the droughts on the forest to project scenarios to 2010. Aguiar et al. (2016) estimated forest degradation scenarios to 2050, however, without modeling the degradation driving factors.

This paper presents an innovative approach to create future scenarios degradation and CO_2 emissions, adapting and combining a land change (LuccME) and a bookkeeping model (INPE-EM). This approach allowed us to explore socio-economic and environmental factors that influence forest degradation spatial distribution and project future scenarios of degradation and CO_2 emissions for the Brazilian Amazon.

4.2 Methods

To discuss scenarios of CO2 emissions from forest degradation in the Amazon in the period 2019 to 2050, we combined a spatially explicit land use modeling approach with the CO2 emissions model INPE-EM (AGUIAR et al., 2012, 2016; ASSIS et al., 2020). We use the LuccME land use modeling framework to generate the annual land cover maps until 2050 and INPE-EM model to estimate the CO2 emissions, considering the clear-cut deforestation and forest degradation processes, as illustrated in Figure 4.1.

4.2.1 Modeling tools

4.2.1.1 LuccME

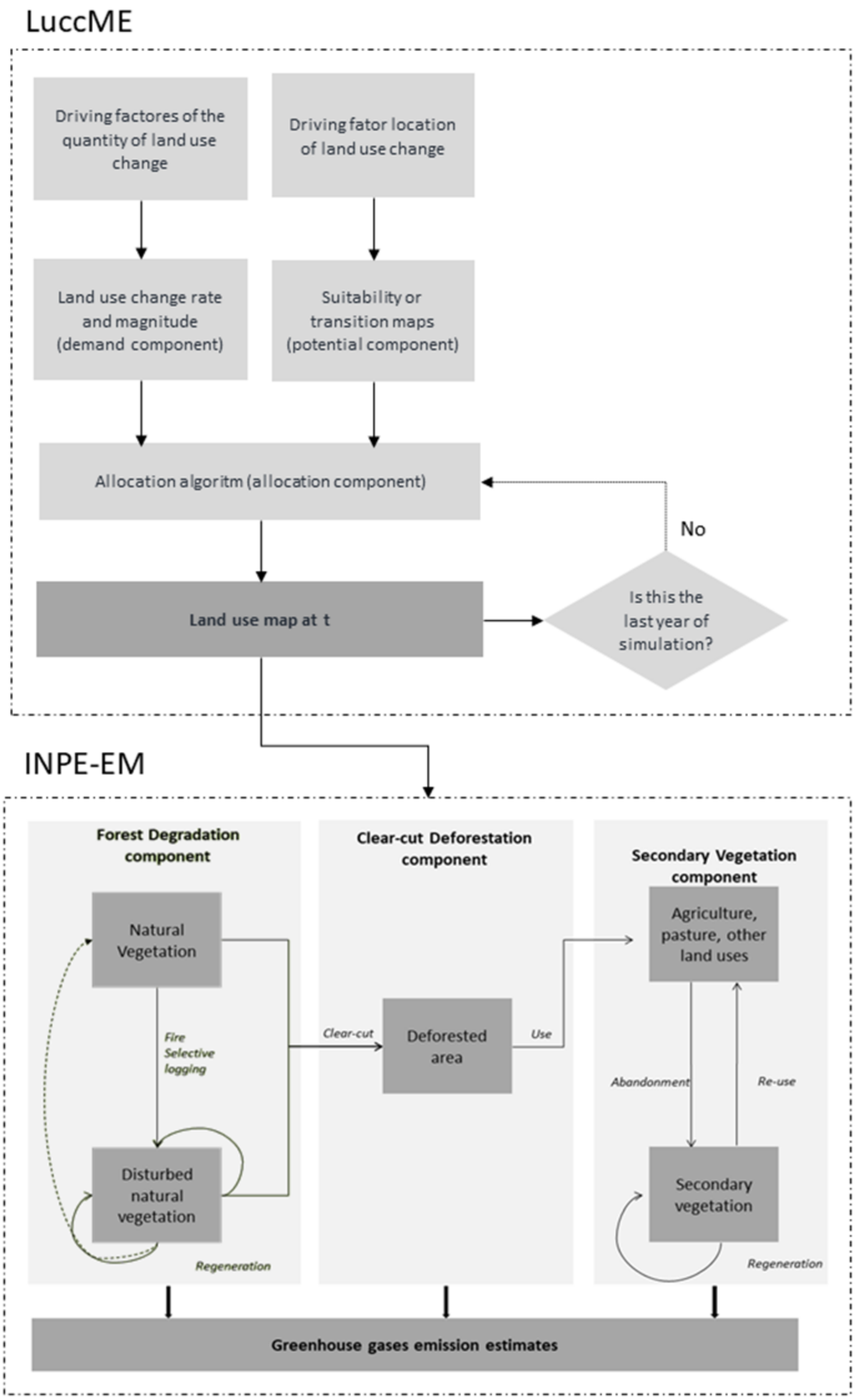
LuccME is an open-source framework for the development of dynamic spatially explicit land-use and cover change models. This type of model can describe the evolution of land use and cover spatial patterns over time, quantifying its driver factors (VERBURG et al., 2004) and spatially allocating the demand for change according to the potential of each cell. In general, we can divide these models into three components: demand, potential, and allocation. The Demand Component defines the amount of change that will be allocated by the model at each time step (VERBURG et al., 2002; AGUIAR et al., 2014). Demand can be calculated from the analysis of historical trends, assumptions arising from scenarios construction, or economic models (VERBURG et al., 2002; AGUIAR, 2006). The Potential Component is based on a set of explanatory variables, mainly related by empirical methods, to calculate the suitable changes for each cell, defined by the demand component. The Allocation component is composed of computational mechanisms that establish competition through decision rules to allocate demand according to the potential of each cell at each model time step. LuccME separates these components responsible for calculating demand, potential and allocation mechanisms, and implements different components, according to the concepts of the different models found in the literature. We used the LuccME components derived from the CLUE model for continuous land-use variables (VELDKAMP; FRESCO, 1996) to generate annual degradation maps.

4.2.1.2 INPE-EM

INPE-EM is a carbon emission model (AGUIAR et al., 2012) based on the bookkeeping model proposed by Houghton et al. (2000) and aims to generate annual estimates of emissions of greenhouse gases (GHG) by the land cover change in a spatially explicit way. It is composed of three components: a) clear-cut deforestation, b) secondary vegetation, and c) forest degradation, which permits to represent emission processes in an integrated way (AGUIAR et al., 2016). In this Chapter, we used the degradation component modified by Assis et al. (2020) which improve the representation of the biomass changes following a degradation event and allows the use of different growth curves to represent the regeneration of the AGB and allow the use of multiple AGB loss factors in the same model.

We considered the 2nd order emissions estimates provided by INPE-EM, which represent the gradual process of liberation and carbon absorption along several years after deforestation events and therefore carry the influence of lagged emissions due to historical processes that occurred in previous years.

Figure 4.1 - LuccME modeling framework generates the annual land use maps, and INPE-EM represents the degraded forest dynamics and calculates the CO_2 emissions derived from this process.



Source: Adapted from INPE (2020d) and Assis et al. (2020).

4.2.2 Study area and input data

Our study area is the Brazilian Amazon, limited to the area monitored by PRODES system (INPE,2020a), which corresponds to approximately 4,000,000 Km². We used INPE monitoring systems, PRODES, DEGRAD, and DETER as our historical land cover sources. PRODES System (INPE, 2020a) identifies clear cut deforestation using satellite monitoring in the Brazilian Legal Amazon since 1988 and is considered by the Brazilian government the official data for Amazon deforestation. Once an area is identified as deforested, it is not monitored in the following years, even if these areas are eventually abandoned.

DEGRAD system identifies forest exposed to fires and disordered selective exploitation in the areas monitored by PRODES. Degradation, unlike deforestation, is mapped in the year in which it occurred but does not remain represented in the following year. In other words, while deforestation in 2007 corresponds to accumulated deforestation up to that year, degradation 2007 corresponds to degradation that occurred solely that year, without considering what happened in previous years. This is because degradation is not a full land cover modification. Thus, the same area can suffer degradation repeatedly and remain considered as a forest. PRODES and DEGRAD generate annual products based on Remote Sensing imagery acquired from August of the prior year to July.

DETER B maps deforestation and other changes in forest cover and was used to complete the degradation temporal series, because DEGRAD System is only available until 2016. To be compatible with the definitions of areas mapped by DEGRAD, we used the DETER B "Degradation" and "Burnt scar" classes (INPE, 2020b). We also considered the period from August 1st of the previous year to July 31st for each year of analysis, similar to PRODES and DEGRAD.

To represent the degradation through a spatially explicit model, we organized a set of variables that could be related to forest degradation, based on the literature and in the results obtained in the previous Chapters of this thesis. These variables were integrated into a cellular space of 25x25 Km² to make compatible information from different sources and formats. The cellular space (COUCLELIS, 1985) is a matrix structure where each cell is associated with several types of attributes, allowing to relate the vector and raster data in a single data layer within a Geographic Information System. Table 4.1 shows the data set, its source, and how it was stored in the cellular space.

Table 4.1 - Variables and Data Sources.

Variable	Representation in the cellular space	Source
Degradation	Percentage of the cell degraded at year t	DEGRAD and DETER (INPE, 2020a; INPE, 2020b)
Historical deforestation	Percentage of the cell deforested until the previous year t (t-1)	PRODES (INPE, 2020a)
Recent deforestation	Percentage of the cell deforested at year t	PRODES (INPE, 2020a)
Water deficit anomaly	Water deficit anomaly at year t	(HARRIS et al., 2014; KOBAYASHI et al., 2015)
Slope	Slope average in the cell	Topodata (INPE, 2020e)
Fertility	Fertility average in the cell	MMA (2020a)
Roads	Euclidean distance to the nearest road	DNIT (2020)
Connection to markets	Distance to Sao Paulo or Brazilian North East considering the paved and unpaved roads	Aguiar (2007), Aguiar (2016), DNIT (2020)
Railways	Euclidean distance to the nearest railways	DNIT (2013)
Hidroways	Euclidean distance to the nearest hidroways	ANTAQ (2013)
distance to the wood poles	Euclidean distance to the nearest wood poles	IMAZON (2014)
Mining (Concession)	Euclidean distance to the nearest mining site	ANM (2020)
Small-scale/alluvial ("Garimpo") Mining (Concession)	Euclidean distance to the nearest mining site	ANM (2020)
Urban centers	Euclidean distance to nearest urban centers with more than 10 thousand inhabitants	IBGE (2012)
Rural settlements	Percentage of the cell coverage by rural settlements	INCRA (2020)
Indigenous territories	Percentage of the cell coverage by Conservation	FUNAI (2020)
Conservation units	Percentage of the cell coverage by indigenous territories	SNUC/MMA (2020)
Hydroelectric plants under construction or operation	Euclidean distance to hydroelectric plants under construction or operation	ANEEL

4.2.3 LuccME parametrization

For the LuccME parametrization, we divided the study area into 3 (three) different land cover classes: forest, degradation, and others, which includes non-forest areas and areas classified as "deforested" by the PRODES System (INPE, 2020). The "others" class is not simulated by the model but is considered a "mask" applied over the study area, which is updated every year.

The land use classes were represented in the cellular space by the percentage of each one contained in each cell. The period considered in the model is from 2007 to 2050, distributed as follows: i) 2007 to 2011: used for potential calculation, ii) 2012 to 1018: model calibration and validation, iii) 2019 to 2015: model simulations.

4.2.3.1 Demand

We use LuccME "*PreComputedValues*" Component, in which we externally calculate the demand and inform to the model the expected area for each land cover in each year. The degradation demand corresponds to the annual degradation area indicated by DEGRAD. The forest area for each year is the forest area (considered in the respective PRODES year) minus the degraded area that year.

4.2.3.2 Potential

To spatially distribute the demand for each land cover class in the model domain, LuccME also calculates the potential of occurrence of a given land cover class based on linear regression, spatial regression, logistic regression, or based on samples, which can be used according to the user needs, in addition to allowing the incorporation of new methods (AGUIAR, et al 2012).

In this work, we use the potential component *PotentialCSpatialLagRegression*, based on spatial regression (ANSELIN; SYABRI; KHO, 2010), where the dependent variable is influenced by its occurrence in the neighborhood, since changes in land use/cover in an area tend to spread through neighboring regions. This component allows us to dynamically update the potential for changes at each time step, considering the temporal changes in the spatial drivers and also the occurrence of degradation in previous years.

The LuccME potential in each cell is given by Equation 4.1:

$$Potential = Spatial\ Regression - Land\ Use\ Area\ in\ the\ cell \qquad (4.1)$$

The spatial regression (Spatial Lag component) is given by Equation 4.2:

$$Y = \rho WZ - X\beta + \varepsilon \qquad (4.2)$$

Where:

W = Spatial proximity matrix
ρ = Measure of spatial correlation
Z =Dependent variable in the year t-1
X= Independent variables
β = Beta coefficient
ε = Constant

LuccME existing components were derived from the CLUE family, which works with structural models, i.e., it models the relationship between the land use patterns at a giving time and spatial drivers. For example, the deforestation area in 2015. However, degradation is not cumulative, different from deforestation it can repeatedly occur in the same area. For this reason, we adapted the component so that the potential in each cell could be calculated directly from the regression values. Table 4.1 presents the list of potential spatial drivers we considered in our analysis.

For the construction of the spatial regression model, we weighted the degradation in each cell by its respective forest area to avoid contamination by deforested and non-forest data. Therefore, we excluded from statistical analysis cells whose forest percentage was equal to zero. We also performed a Spearman correlation analysis (SPEARMAN, 1904) between the variables in our dataset to prevent those factors with a correlation coefficient above 0.6 were used in the same regression.

We performed the statistical analysis for degradation considering the period from 2007 to 2011 and adjusted the explanatory variables to this date. Based on the literature (BRANDO et al., 2014; FARIA et al., 2017) and on the analysis described in Chapter 2, which pointed out the importance of extreme drought events in the spatial distribution of degradation, we explore the degradation drivers considering two distinct periods: i) from 2007 to 2010 (non-drought years) ii) 2011 (year of extreme drought). The 2011 year was chosen because it represents the influence of the extreme drought of 2010 (LEWIS et al., 2011). We emphasize that, according to DEGRAD methodology, the degradation mapped in a given year goes from August of the previous year to July of that year. Thus, 2011 degradation refers to the period from August 2010 to July 2011, which was largely affected by the extreme drought of 2010.

We adapted LuccME to alternate between both regressions during model execution using an attribute that indicates whether the year was a "non-drought" or "drought." To classify all years, according to this rule, we set the "2010 average water deficit anomaly" as a threshold. Years with an average value lower than the "2010 average water deficit anomaly" were considered "drought," while the others were considered "non-drought."

The model fit was assessed using the multiple determination coefficient values (R^2) and the AIC criterion (AKAIKE, 1974) that show the fit of the model (ANSELIN; SYABRI; KHO, 2010).

4.2.3.3 Allocation

Once we have defined the model demand and potential parameters, we applied the allocation component (*AllocationCClueLike*) based on CLUE (VELDKAMP; FRESCO, 1996) to allocate the land cover classes annually, for the period from 2012 to 2018. The model was configured so that, each year, both the forest and degradation classes may increase or decrease the occupied area within the cells, reflecting the behavior observed in the real data. The "others" class was adjusted annually to incorporate the deforestation that occurred over the years.

Once we defined all the parameters, we ran the model for the period from 2012 to 2018 to assess whether we were able to capture the behavior observed in the degradation data. To evaluate the results, we used the validation method of adjustment of multiple spatial resolutions (COSTANZA, 1989), which establishes the degree of similarity between the simulated map and the real map in different resolutions. This approach allows us to evaluate both location errors in the model resolution itself, and spatial pattern errors, degrading the resolution of the maps.

4.2.4 INPE-EM parametrization

INPE-EM combines land cover, and biomass change maps to calculate CO_2 emissions. We use the annual maps of degradation and deforestation resulting from the simulation with LuccME to estimate CO_2 emissions from 2016. Estimates of CO_2 emissions up to 2016 were generated in Chapter 3 of this thesis, where the description of the adopted data and parameters can be found in Table 3.1.

4.2.5 Scenarios

To generate the degradation scenarios, we rely on the deforestation and secondary vegetation scenarios developed by (AGUIAR et al., 2016), based on the Story and Simulation (SAS) approach (Alcamo & Ribeiro, 2001), which combines qualitative and quantitative elements. These scenarios were produced with the participation of stakeholders in structured workshops (FOLHES et al., 2015) to discuss desired and undesirable visions of future related to natural resources, social development, economic activities, infrastructure, technology, and the political and institutional context. From these visions of the future, trajectories were constructed to reach each of them, thus defining the scenarios: i) "sustainability," with improvements in the socio-economic, institutional and environmental dimensions and ii) fragmentation with the weakening of the socio-environmental dimension and chaotic urbanization and iii) "middle of the road." These scenarios are aligned with the Intergovernmental Panel on Climate Change (IPCC) Shared Socioeconomic Pathways (SSP) 1, 3, and 2, respectively (VAN VUUREN et al., 2012; O’NEILL et al., 2014). In this work, we considered the "sustainability" and fragmentation scenarios.

These four points were considered to quantify the conceptual scenarios: (a) environmental law enforcement; (b) future clear-cut deforestation; (c) secondary vegetation dynamics in abandoned areas after clear-cut deforestation; and (d) changes in the major spatio-temporal deforestation drivers: Conservation units and roads infrastructure (AGUIAR;

CÂMARA; ESCADA, 2007). We adopted all these premises described in Aguiar et al. (2016) in the development of forest degradation scenarios. The "sustainability" scenario considered that political and institutional conditions would favor the reduction of deforestation by 2020, reaching an average of 1000 Km^2 / year from 2025 onwards. This scenario also considers the regeneration of all illegally deforested areas and assumes that the secondary vegetation will increase from 22% to 35% from 2015 to 2030 and will no longer be periodically removed. The fragmentation scenario assumed a return of high rates of deforestation, similar to those before 2004, of 15,000 Km^2 / year. The dynamics of secondary vegetation remains as it is today. In this scenario, the National Forest Code is not respected, and secondary vegetation follows its current dynamics, with a high rate of deforested land abandonment and a short cutting cycle in consolidated areas.

To define forest degradation rates in each of the scenarios, we applied the results of Fonseca et al. (2019). They projected forest degradation until 2100 using Aguiar et al. (2016) land use scenarios and climate scenarios based on Representative Concentration Pathways RCP4.5 and RCP 8.5 (IPCC, 2013). We calculated the annual amount of degradation in each scenario by applying the projected growth rate for each scenario to the annual reference value, given by the average degradation between 2007-2018. To better compare land use scenarios, we used only RCP 4.5 in the analyzes, which considers the stabilization of the radiative forcing at 4.5 Wm^{-2} in the year 2100. We, therefore, adopted Fonseca et al. (2019) degradation growth projections Fonseca, who combined i) RCP 4.5 and the "sustainability" scenario and ii) RCP 4.5 and the fragmentation scenario.

Finally, we used the annual degradation maps generated for each scenario up to 2050 to estimate the CO_2 emissions resulting from this process. For this, we used INPE-EM (AGUIAR et al., 2012) with the parameters of deforestation and secondary vegetation adopted in Aguiar et al. (2016) scenarios and the parameters of degradation described in Chapter 3 of this thesis.

4.3 Results

Section 4.3.1 shows the modeling procedure results. Section 4.3.1 presents the variables that best explained the degradation between 2007 and 2011. Then, Section 4.3.2 presents the result of the simulation in the validation period (2012 to 2018) and the model goodness of fit. Section 4.3.3 deals with CO_2 degradation and emissions scenarios.

4.3.1 Spatial regressions

We developed three Spatial Lag regression models to build the spatially explicit model: a model for the (non-degraded) forest, a model for the forest degradation in years with extreme drought, and a model for the forest degradation in non-drought years. Table 4.2 describes these models and their R^2 and AIC.

We obtained 0.86, 0.60 e 0.46 of R^2 score to the forest, degradation in extreme drought years, and degradation in non-drought years, respectively. The variables that best explained the permanence of the non-degraded forest were: percentage of Conservation Units, Indigenous Territories, and distance to Roads and Urban Centers. Degradation was best explained by Historical Deforestation and Connection to Markets in non-drought years, and by Water Deficit Anomaly and Recent Deforestation in drought years. The spatial coefficient, which measures the spatial correlation of each dependent variable was significant and higher than 0.75 in all models, meaning that degradation is also a spatially concentrated process, as deforestation (AGUIAR et al., 2007).

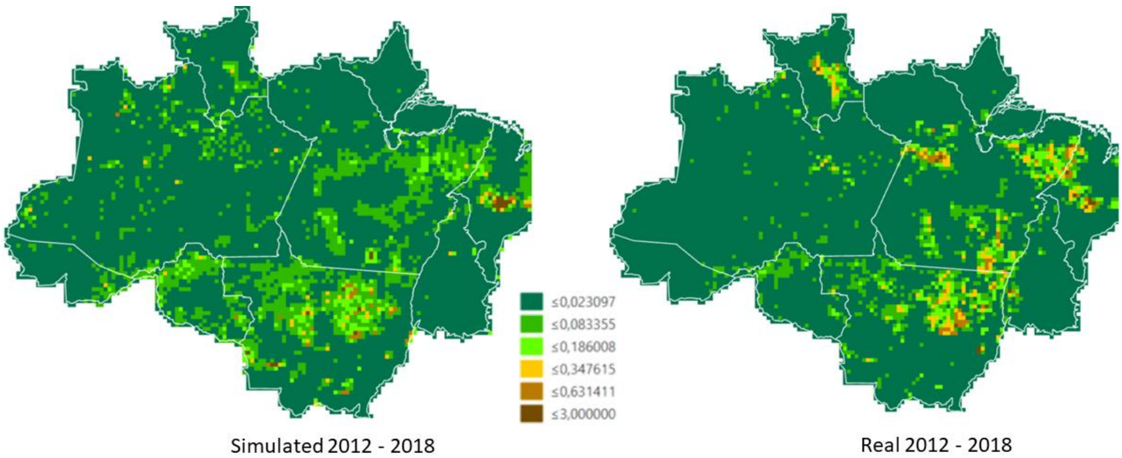
Table 4.2 - Spatial Lag regressions.

Non-degraded Forest			**Degradation in normal precipitation years**			**Degradation in extreme drought years**		
R^2: 0.86			**R^2: 0.59**			**R^2: 0.46**		
Akaike (AIC): -8031			**Akaike (AIC): -16099.5**			**Akaike (AIC): -27777.8**		
Variable	**Coefficient**	**Prob.**	**Variable**	**Coefficient**	**Prob.**	**Variable**	**Coefficient**	**Prob.**
Spatial Coefficient	0.90	0.000	Spatial Coefficient	0.824	0.000	Spatial Coefficient	0.773	0.000
CONSTANT	-0.111	0.000	CONSTANT	0.066	0.000	CONSTANT	0.000	0.102
Conservation units	0.052	0.000	*Historical deforestation*	0.024	0.000	*Water deficit anomaly*	-2.834e-005	0.000
Indigenous territories	0.057	0.000	*Connection to markets*	-0.004	0.000	*Recent deforestation*	0.837	0.000
Roads	0.006	0.000						
Urban centers	0.008	0.000						

4.3.2 Land use change model validation

From the definitions adopted, described in Section 4.2, and the results obtained in the spatial regression model, we ran the model in LuccME from 2012 to 2018 and compared the simulated degradation maps with the real degradation data to verify the model adjustment. Figure 4.2 presents the percentage of degradation in 25 x 25 Km² cells maps for simulated by the model (a) and inferred by DEGRAD and DETER data (b). The model fit reached 66.6% when comparing the patterns of both maps.

Figure 4.2 - Percentage of degradation in 25 x 25 Km² cells from 2012 to 2018 a) Simulated by LuccME, b) Real data.



Source: Prepared by the author.

In general, the model captured all the main hot spots of degradation in the period. The model was able to represent the degradation patterns in the north of the state of Mato Grosso, a region with most of the degradation observed in the period. In northern Rondônia, Maranhão, Pará, and Roraima, the patterns were well represented. However, the model overestimated the volume of degradation in Rondônia and underestimated in Pará and Roraima, especially in southeastern Pará.

Based on these models, which we consider to capture relatively well the degradation process we proceeded to explore future scenarios.

4.3.3 Forest degradation and CO_2 emission scenarios

Figure 4.2 shows the maps containing the total percentage of degradation in 25x25 Km² cells, which occurred from 2019 to 2050 in scenarios sustainable and fragmentation. As the maps represent the sum of the degradation that occurred in each cell within the period of the scenarios, values greater than 1 (one) may occur, which indicates that this cell has suffered recurrent degradation.

In both scenarios, we can observe repeated degradation events in the north of Mato Grosso and the southeast and northeast of Pará, being the areas most affected by the degradation. We emphasize that these areas also should be the most affected by deforestation by 2050, according to Aguiar et al. (2016) scenarios. In other words, in these regions, an intensification of the patterns already observed today is expected, with a large part of the forest exposed to deforestation or forest degradation.

It is also observed that almost all forest cells in the region are exposed to some level of degradation until 2050. At the end of the simulation, most of them presented a portion of up to 10% of forest degradation. However, in the sustainable scenario, it is still possible to observe regions of intact forest, especially in eastern Amazonas.

Using INPE-EM, we estimated the carbon balance in these scenarios. Within the scenarios period (from 2019 to 2050), CO_2 net emissions totaled 0.74 Gt CO_2 in sustainable scenario e 22.63 Gt CO_2 in fragmentation scenario, considering the emissions from forest degradation and deforestation, absorption from degraded forest recovery, and secondary vegetation growth and emission from the cut of secondary vegetation itself. Total amounts estimated correspond to 2% (sustainable scenario) and 62% (fragmentation scenario) of the net emissions from 1960 to 2012.

The forest degradation is projected to emit 6.2 Gt CO_2 and 9.1 Gt CO_2 in sustainable and fragmentation scenarios, respectively, which represent 42.8% and 23.4% of the 14.6 Gt CO_2 and 39.1 Gt CO_2 gross emissions in sustainable and fragmentation scenarios. The aggregate effects of the post-disturbance regeneration vary widely between the scenarios. While in fragmentation it represents 93.7% of the forest degradation emissions, in “sustainable,” the absorption from forest recovery surpasses the emissions from degradation in the same period, corresponding to 111% of it. Table 4.3 summarizes these results.

Table 4.3 - CO_2 balance simulated in the scenarios.

CO_2 (Gt CO_2)	Period	Sustainable Scenario	Fragmentation Scenario
Net emissions	1960-2018 (58 years)	36.55	36.55
	2019-2050 (31 years)	0.74	22.63
Degradation emissions	1960-2018 (58 years)	4.10	4.10
	2019-2050 (31 years)	6.23	9.13
Total emissions	1960-2018 (58 years)	43.45	43.45
	2019-2050 (31 years)	14.58	39.09
Degraded forest regeneration	1960-2018 (58 years)	-1.98	-1.98
	2019-2050 (31 years)	-6.94	-8.55

4.4 Discussion

This paper presented an innovative approach to creating future scenarios of degradation and CO_2 emissions, adapting and combining a land change (LuccME) and an emission model (INPE-EM). We organize the discussion in three parts. We first discuss the land change modeling implications of our results, then the spatial drivers of change, and finally, the scenario results.

4.4.1 Modeling different behavior in drought and non-drought years

Our results demonstrated that the degradation assumed two distinct behaviors over the period studied, one for years of extreme droughts and another for the non-drought year. For this reason, we modified the LuccME framework to use two different regressions for the same use (component *DegrationPotential*). For this, we include a decision rule that makes the model alternate between both regressions throughout the simulation.

This approach allowed exploring socio-economic and environmental factors that influence forest degradation spatial distribution and project future scenarios of degradation and CO_2 emissions to the Brazilian Amazon. The adaptations made in LuccME (detailed in Section 4.2) to represent the degradation process can be used in processes with similar characteristics.

4.4.2 Degradation driver factors

Among the various socio-economic and environmental factors analyzed in this work, historical deforestation and the connection to markets (AGUIAR; CÂMARA; ESCADA, 2007; AGUIAR et al., 2012) were the ones that better explained the spatial distribution of degradation in non-dry years, reinforcing the understanding of the influence of historical deforestation on degradation, discussed in Chapter 2. The fragmentation caused by deforestation exposes the forest along the edges (COCHRANE, 2001), due to environmental or (COCHRANE; BARBER, 2009; ALENCAR et al., 2015), anthropic factors (BARLOW et al., 2020). Environmental factors include the increase of flammability, wind speeds, and insolation rates. Anthropic factors include facilitating the flow of wood and the management of areas deforested with the use of fire, which can spread into the forest.

The market connects local activities, such as crops, for example, to regional and global processes (VERBURG; ELLIS; LETOURNEAU, 2011; MEYFROIDT et al., 2013). Aguiar et al. (2016) point out the connections to markets as an important factor in capturing the spatial patterns of the new frontiers in Brazil. Our results also pointed out the importance of this driver to the degradation process. “Connectivity to markets" variable was created calculating the distance to Sao Paulo or Brazilian North East considering the paved and unpaved roads. By considering the distance between two points weighted by the existence of highways, it combines consumer centers and roads to compose a connectivity indicator.

In years of extreme drought, the analyzes pointed to water deficit anomaly and recent deforestation as the major drivers of forest degradation. Several authors have pointed out the importance of the relationship between water deficit in years of extreme drought (BRANDO et al., 2014; FARIA et al., 2017; ARAGÃO et al., 2018), as shown in Chapter 2. In these years, the proximity to recent deforestation (which occurred in the same year) gains space due to the escape of fires resulting from the cleaning of deforested areas. As the areas are drier, the fire spreads more easily, entering the forest areas.

4.4.3 Land use/cover change and CO_2 emission scenarios

This work presented innovative scenarios of emissions from forest degradation, considering two land use scenarios, based on the sustainable and fragmented scenario of Aguiar et al. (2016), and the "fragmented + RCP 4.5" and "sustainable + RCP 4.5" scenarios of Fonseca et al. (2019), which had previously simulated forest degradation scenarios from land use changes and climate change. Le Page et al. (2017) also developed degradation scenarios based on Land Use and climate change scenarios for the Amazon. Still, both scenarios do not include the emissions resulting from this process. Aguiar et al. (2016) modeled the emissions resulting from forest degradation, but the degradation was not spatially modeled in the scenarios. The scenarios presented here show a wide variation in the carbon balance between the two scenarios and bring gains in the understanding of how changes in deforestation/secondary vegetation/degradation patterns can affect emissions in the Amazon.

In particular, given the importance of deforestation as a driver factor in both the dry and normal years, deforestation resulting from these scenarios has a substantial impact on degradation results. The resumption of growth in deforestation rates recorded by PRODES in recent years takes us away from the sustainable scenario, bringing us close to the fragmented scenario.

To explore the impact of different land use change scenarios on emissions from deforestation, we chose to work with only RCP 4.5. However, as an improvement for future work, we suggest the use of different climate scenarios.

4.5 Conclusion

In this Chapter, we developed an innovative approach to creating future scenarios degradation and CO_2 emissions, adapting the land change modeling framework LuccME and combining it to INPE-EM emission models. This approach allowed exploring socio-economic and environmental factors that influence forest degradation spatial distribution and project future scenarios of degradation and CO_2 emissions to the Brazilian Amazon.

We built a sustainable and fragmentation land use scenarios based on Aguiar et al., (2016) and estimated their impacts on CO_2 emission. In both scenarios, we observed repeated degradation events in the north of Mato Grosso and southeast of Pará, intensifying the existing patterns in the region. It was also observed that almost all forest cells in the region are exposed to some level of degradation until 2050. At the end of the simulation, most of them presented a portion of up to 10% of forest degradation. However, in the sustainable scenario, it was still possible to observe regions of intact forest, especially in eastern Amazonas. Our results also showed that while net CO_2 emissions from 2019-2050 added up 0.74 Gt CO_2 in the sustainable scenario, in fragmentation scenario, this value reached 22.63 Gt CO_2.

5 GENERAL DISCUSSION

This section discusses, in an integrated way, the core aspects of the results obtained in this thesis. Our results in Chapter 2 pointed that in dryer years, the spatial relation between degradation and drought conditions areas exceeds 87.5%, in consonance with previous studies in the literature (ALENCAR et al., 2015; ANDERSON et al., 2015; ARAGÃO et al., 2018; BRANDO et al., 2020b). Although several works discuss the influence of water deficit both in the amount and distribution of forest degradation in drought years, no papers are discussing this phenomenon in non-droughts years. But the analysis of the entire period indicates a weak link between degraded areas and drought conditions in years with normal precipitation. In these years, this relationship does not exceed 32%, which indicates that drought responses individually are not enough to explain the degradation in a particular year, as pointed out by Marlon et al. (2009). Therefore, we obtained the best statistical and land change model calibration in Chapter 4 considering diverse socioeconomic and environmental variables that could explain the forest degradation spatial distribution from 2007 to 2018, when we used separate regression models for drought and non-drought years. In the drought years the water deficit anomaly, together with recently deforested areas, was an important driver, while the degradation patterns in non-drought years are better explained by historical deforestation and connection to markets.

Furthermore, our analysis in Chapter 2 showed a strong link between degradation and historical deforestation. Considering the period from 2006 to 2018, on average, 82% of the degradation happened in areas with historical deforestation along its 5x5 cells neighborhood. This correspondence reaches more than 80% in all years (except from Aug2011 to Jul2012 and from Aug2013 to Jul2014). It can indicate the influence of deforestation in both the spatial pattern and the amount of degradation. These results do not agree with Aragão et al. (2018) that pointed out the decoupling between degradation and deforestation during the 2015 extreme drought. It was probably because we extended our study to the surroundings, along with a 5x5 cell neighborhood, and considered the historical, instead of recent clear cut deforestation data. We made this choice because we understand that the influence of deforestation in forest degradation due to border effect

(SILVA JUNIOR et al., 2018) and exposure to anthropogenic areas (BARLOW et al., 2020), discussed in Chapter 2, cannot be measured from deforestation that occurred only adjacent and in the same year of degradation. The clearing of deforested areas is not always done immediately, so that in the first year its effects are felt in the surrounding forest. Likewise, the impacts of areas occupied by other land uses, such as livestock, can also be felt by the forest over the years, since the cleaning process of these areas is periodical. This result illustrated the importance of spatial and temporal multiscale analysis.

On the other hand, on average only 8% of the degraded area was converted to clear cut deforestation, indicating that, although the historical deforestation influences the degradation occurrence, there is a decoupling between them when considering degradation as a starting point for deforestation, as demonstrated in Chapter 3. The decrease in Brazilian Amazon deforestation rates since 2004 may have contributed to this situation. Additionally, 61% of the degraded areas were in a regeneration path without subsequent disturbances in the following ten years.

This dynamic impacts the CO_2 emissions, especially in the importance of the absorption by degraded forest recovery in the carbon balance in the Brazilian Amazon. From 2007 to 2016 2694 Mt CO_2 were emitted from forest degradation, while the absorption due to degraded area recovery reached 1822 Mt CO_2. Although the prevalence of this trajectory can have positive effects on the carbon balance compared to the other trajectories, these events may drive long term consequences altering forest structure and composition, leading to the impoverishment of forests and further increase flammability for several years (BARLOW; PERES, 2008). However, the recent rise of clear-cut deforestation rates (INPE, 2020a), associated with the evidence of an increase of droughts due to climate change (MARENGO et al., 2018), pose considerable uncertainty about the future of these processes. Besides, we considered only the AGB loss in the estimates of CO_2 emissions from degradation, which may underestimate them.

5.1 Uncertainties and limitations

It is important to note that we built all of the analyzes presented in this thesis based on the degradation data from DEGRAD. These data have specificities that need to be considered when evaluating the uncertainties of our results. DEGRAD identify areas with loss in forest cover without conversion to clear-cut deforestation in PRODES forest areas. DEGRAD uses Landsat program imagery with 30 meters of spatial resolution and minimum mapping area of 6.25 ha.

This also implies that we are considering as degradation any disturbance that changes the structure of the forest without converting it to clear cut deforestation, that is, unique events are also considered as “forest degradation”. However, we were careful to use parameters compatible with this methodological decision in the analysis and emission model. The parameters of loss / regrowth of vegetation due to forest degradation at INPE-EM, for example, are considered annually and are supported by work that makes this distinction of recurrence or not of disturbances in a given area.

6 CONCLUSION

The objectives of this thesis were to investigate the factors underlying the spatio-temporal distribution of forest degradation in the Amazon in recent years, and how they impact CO_2 balance in the region. To achieve this objective, we first quantified the relationships between forest degradation, droughts, deforestation, and protected areas indicators in the Brazilian Amazon over the years in Chapter 2. It allowed us to access how these relationships were in years with distinct situations. Then, we analyzed spatio-temporal trajectories of forest degradation recovery and conversion to other land uses in the region in Chapter 3, which made it possible to understand the dynamics of degradation in the Amazon.

Adapting INPE-EM Degradation Component also in Chapter 3 allowed us to represent the biomass dynamics in the degradation process, and represent an integrated analysis of the CO_2 emissions and absorptions from land cover changes over the period. Finally, we developed an innovative approach to creating future scenarios degradation and CO_2 emissions in Chapter 4, adapting a land change (LuccME) framework and combining it to emission models (INPE-EM). This approach allowed exploring socio-economic and environmental factors that influence forest degradation spatial distribution and project future scenarios of degradation and CO_2 emissions to the Brazilian Amazon.

6.1 Synthesis of the answers to research questions

Six research questions were addressed to investigate the degradation process in this thesis. The answers to these questions are presented below.

(a)How is the spatial-temporal distribution of forest degradation related to water deficit in drought and non-drought years?

Our results from Chapter 2 and 4 indicate that the spatial distribution of degradation flips completely under the two regimes (drought years and non-drought years). While the spatial distribution follows the water deficit pattern regardless of historical patterns in a drought year, in non-drought years, it is explained by multiple other socio-economic, in particular, proximity to deforestation. For example, the results reveal that although more than 80% of forest degradation occurred in areas under drought conditions in years with experienced extreme droughts events, the perceptual is only 33.2% when the total period (2007-2018) is considered.

(b)How do past deforestation spatial patterns influence this distribution?

Our results indicate a strong relationship between degradation and previous deforestation. On average, 82% of the degraded area had historical clear-cut deforestation in its surroundings. If, on the one hand, we can observe a large temporal variation in the relationship between water deficit and degradation, on the other hand, this relationship has been high in all years of analysis with historical deforestation.

Another important result relates to the distinct role of deforestation between drought and non-drought years. While in the non-dry years the factors that best explained the degradation were the history of previous deforestation and connection to the market (see below the answer about additional factors), in the dry years it was better explained by the anomaly of water deficit and recent deforestation, that is, that which occurred in the same year of the degradation.

However, the linkage is not bi-directional. Our trajectories analysis showed that, in the analyzed period, only a small percentage of degradation became clear-cut deforestation. Our analysis performed in Chapter 3 showed that only 13% of the degradation was converted to clear cut deforestation between 2007 to 2016, while 61% of the areas experienced only one degradation event. Besides, this percentage has decreased in the period, possibly because deforestation rates have decreased when compared to the initial year (2007). We must consider that the period analyzed in the trajectories experienced low rates of deforestation and recurrence of extreme drought events and, therefore, there is great uncertainty about how this process will develop in the coming years.

(c)How do protected areas been affected by forest degradation?

Even though Indigenous Territories and Conservation Units play an essential role in the environmental preservation of the region, they are not impervious to forest degradation. We measured the proportion of degradation that occurred in protected areas from 2007 to

2018 (Chapter 2). On average, 25% of the degradation occurred inside Indigenous Territories and 9% in Conservation Units.

(d)How much of degraded areas become clear-cut deforestation and how the combination of these two processes affects the biomass and CO_2 emissions?

We calculated the CO_2 emissions from 1960 to 2015 to consider the lagged emission of this process. Within the entire period, emissions amount to 34.9 Gt CO_2, considering the emissions from forest degradation and deforestation, absorption from degraded forest recovery, and secondary vegetation growth and emission from the cut of secondary vegetation. The degradation contribution to the gross emissions increased from 3.2% (from 1981 to 2006) to 30.3% (from 2007 to 2016), while deforestation contribution decreased from 91.7% to 57.4%, reflecting both the prevalence of the trajectory of unique events and the period of low deforestation rates.

(e) Which other socio-economic and environmental factors influence the forest degradation spatial distribution?

As discussed above, to capture the spatial distribution of degradation over the years, it was necessary to divide the analyzes into two conditions: non-dry and dry years, as they are different processes, influenced by different variables. Besides deforestation, another influential factor in non-drought years was the connection to markets, which measures the shorter distance to the cities of São Paulo or Recife, considering paved and unpaved roads. This variable is an indicator of occupation, production flow, and infrastructure and also plays an important role in explaining clear cut deforestation patterns. In the dryer years, degradation was influenced by water deficit anomaly and recent deforestation (that occurred in the same year of the degradation event).

(f) Based on these factors, what are the possible impacts of forest degradation in CO_2 emissions in the future?

Based on Aguiar et al., (2016), we built a sustainable and fragmentation land use scenarios and their impacts on CO_2 emissions. In both scenarios, we can observe repeated degradation events in the north of Mato Grosso and the southeast and northeast of Pará, being the most affected areas by degradation. In these regions, an intensification of the patterns already observed today is expected, with a large part of the forest exposed to deforestation or forest degradation. It was also observed that almost all forest cells in the region are exposed to some level of degradation until 2050. At the end of the simulation, most of them presented a portion of up to 10% of forest degradation. However, in sustainable scenario, it was still possible to observe regions of intact forest, especially in eastern Amazonas.

The modeling approach proposed in Chapter 4 adapted the LuccME to represent the degradation process better and combined it with INPE-EM emission model to estimate the CO_2 impacts due to the degradation and deforestation simulated. Our results showed that while net CO_2 emissions from 2019-2050 added up 0.74 Gt CO_2 in the sustainable scenario, in the fragmentation scenario, this value reached 22.63 Gt CO_2.

6.2 Policy implications

Based on the results discussed above, we indicated policies implications as follows:

- The strong relationship between degradation and deforestation becomes especially relevant at a time when we see the return of high rates of deforestation in the Amazon.
- The importance of Conservation Units and Indigenous Territories in the protected forest from clear cut deforestation is also efficient to restrain forest degradation.
- Public policers should be prepared for drought and forest fires in unusual areas due to climate change.

6.3 Future works

Although this thesis has advanced in the knowledge of forest degradation process in the Brazilian Amazon and its impacts on CO_2 emissions, much can still be done in this perspective. Thus, we point out proposals for the continuity of this work:

- Test the relationship between degradation and other land use indicators based on recent deforestation or livestock, for example.
- Use different biomass maps, factors of biomass loss due to degradation and regrowth curves to estimate CO_2 emissions, since there are uncertainties regarding biomass and its dynamics after a degradation event.
- Build new scenarios of forest degradation, exploring other climate scenarios or new premises about land use changes.
- Analyze future scenarios from the perspective of degradation trajectories.

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