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CARTOGRAPHY OF THE PIONEER FRONTS AND CONTRIBUTION TO THE ANALYSIS OF DEFORESTATION IN PARÁ

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Abstract

The present study is based on a diachronic cartography of the pioneer fronts in the Brazilian state of Pará, which was used to analyze deforestation patterns between 2002 and 2017. For this cartography, the territory of Pará was divided into cells of 5 km x 5 km, in which the cumulative percentage of deforestation was calculated for each year from 2002 to 2017, with the data being classified in five evolutionary phases of the pioneer front. This cartography permitted the systematic representation of the spatiotemporal dynamics of deforestation in the study area and the evaluation of regional patterns, which allowed the pioneer regions to be delimited and characterized in three principal categories – expansion, stabilization, and consolidation. By relating the pioneer fronts to deforestation rates in each period, it was possible to classify them as consolidated territories, focused on the intensification of agricultural practices, or under expansion, through a strategy of occupation, in addition to areas free of deforestation. The approach adopted in the present study is easy to understand and can provide important guidelines for decision-makers in different administrative spheres, contributing to the formulation of effective measures for the control of deforestation and the sustainable development of the region.

Keywords: Pioneer fronts. Deforestation. Territorial Dynamics. Brazilian Amazon.

Resumo / Résumé

CARTOGRAFIA DAS FRENTES PIONEIRAS E CONTRIBUIÇÃO À ANÁLISE DO DESMATAMENTO NO PARÁ

O presente estudo é baseado em uma cartografia diacrônica das frentes pioneiras no estado do Pará, que foi utilizada para analisar os padrões de desmatamento entre 2002 e 2017. Para esta cartografia, o território do Pará foi dividido em células de 5 km x 5 km, em que foi calculado o percentual acumulado de desmatamento para cada ano de 2002 a 2017, sendo os dados classificados em cinco fases evolutivas da frente pioneira. Essa cartografia permitiu a representação sistemática da dinâmica espaço-temporal do desmatamento na área de estudo e a avaliação dos contrastes regionais, o que permitiu delimitar as regiões pioneiras e caracterizá-las em três categorias principais - expansão, estabilização e consolidação. Ao relacionar as frentes pioneiras às taxas de desmatamento em cada período, foi possível classificá-las como territórios consolidados, voltados para a intensificação das práticas agrícolas, ou em expansão, por meio de uma estratégia de ocupação, além de áreas livres de desmatamento. A abordagem adotada no presente estudo é de fácil entendimento e pode fornecer orientações importantes para tomadores de decisão em diferentes esferas administrativas, contribuindo para a formulação de medidas eficazes para o controle do desmatamento e o desenvolvimento sustentável da região.

Palavras-chave: Frentes Pioneiras. Desmatamento. Dinâmica Territorial. Amazônia Brasileira.

CARTOGRAPHIE DES FRONTS PIONNIERS ET CONTRIBUTION À L'ANALYSE DE LA DÉFORESTATION AU PARÁ

Le présent texte prend en compte une cartographie diachronique des fronts pionniers dans l'état brésilien du Pará, qui a été utilisée pour analyser les schémas de déforestation entre 2002 et 2017. Pour cette cartographie, le territoire de Pará a été divisé en cellules de 5 km x 5 km, dans lequel le pourcentage cumulé de déforestation a été calculé pour chaque année de 2002 à 2017, les données étant classées en cinq phases évolutives du front pionnier. Cette cartographie a permis la représentation systématique de la dynamique spatio temporelle de la déforestation dans la zone d'étude et l'évaluation des contrastes régionaux, ce qui a permis de délimiter et de caractériser les régions pionnières en trois grandes catégories - expansion, stabilisation et consolidation. En reliant les fronts pionniers aux taux de déforestation à chaque période, il a été possible de les classer en territoires consolidés, focalisés sur l'intensification des pratiques agricoles, ou en expansion, à travers une stratégie d'occupation, en plus des zones sans déforestation. L'approche adoptée dans la présente étude est facile à comprendre et peut fournir des lignes directrices importantes aux décideurs dans différentes sphères administratives, contribuant à la formulation de mesures efficaces pour la lutte contre la déforestation et le développement durable de la région.

Mots-clés: Fronts Pionniers. Déforestation. Dynamique Territoriale. Amazonie Brésilienne.

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INTRODUCTION

The ongoing advance in the deforestation of Brazilian Amazon is one of the principal environmental problems facing this region (BRITO et al., 2019; FEARNSIDE, 2017; STRAND et al., 2018). Up to 2019, approximately 20% of the total area of forest of this region had been lost to deforestation (INPE, 2020). In 2005, a total of 19,014 km2 was deforested, a decrease of 32% in comparison with 2004, marking the beginning of a period of decline in the region's deforestation rates, which reached a low of 4,571 km2 in 2012. Subsequently, however, there was a gradual increase in this activity, which grew progressively to reach 10,129 km2 by 2019 (INPE, 2020).

A number of different scholars have attempted to understand the dynamics of the region's deforestation rates, in particular through the analysis of fluctuations in prices and other regulatory mechanisms of the international markets (GIBBS et al., 2016; LAMBIN et al., 2018; PIATTO; SOUZA, 2017) or government interventions, such as the Action Plan for the Prevention and Control of Deforestation in Brazilian Amazon – PPCDAM (MELLO; ARTAXO, 2017). A number of other factors have also been considered important, including the impact of highways (BARBER et al., 2014), land ownership (GOLLNOW et al., 2018; RICHARDS; VANWEY, 2016), the types of agricultural production (FEARNSIDE, 2008; GODAR et al., 2014), and public policy (ARIMA et al., 2014; BÖRNER et al., 2014; PACHECO, 2009).

A number of studies have also emphasized the complexity and scope of the dynamics of deforestation in the region, in the quest for more holistic perspectives. Garrett et al. (2018) and Byrlee; Stevenson; Villoria (2014) evaluated the potential for the avoidance of deforestation through the intensification of land use, while Pacheco; Poccard-Chapuis (2012) highlighted the complexity of cattle ranching, considering its ample spatial dimension. From this perspective, Piketty et al. (2015) demonstrated that the deforestation is associated primarily with local development trajectories and governance mechanisms. Le Tourneau; Droulers (2011) proposed multi-criteria categories and assessment for the understanding and control of the deforestation process, with the aim of compiling indicators of sustainable development. These studies perceive Brazilian Amazon as a frontier region, with the deforestation being among the best-studied phenomena, in the quest to understand its territorial dynamics and its relationship with the occupation process.

The concept of the "frontier" was first adopted by Frederick Turner, in his book The Frontier in American History, published in 1893. This book redesigned the viewpoint of American society on the process of expansion of the country's territory, and influenced Brazil's "March to the West" (ANDRADE, 2010). The French geographer Pierre Monbeig adapted this concept to the analysis of the occupation of the Brazilian states of Paraná and western São Paulo by coffee farmers, formulating new concepts that had a major impact on this academic field, including the pioneer front, the pioneer fringe, and the pioneer march (MONBEIG, 1981). Subsequent authors, including Théry (1976, 2006, 2012), Droulers (2015), Becker (1991, 2004, 2005) and Martins (1996), adapted these concepts to the specific context of the Amazon region.

More recently, the concept of the pioneer front has been employed for the analysis of territorial development (ALBADEJO; TULET, 1996; COY; KLINGLER, 2014; COY; KLINGLER; KOHLHEPP, 2017; ESCADA et al., 2005), the dynamics of land cover and use (ARVOR, 2009; ARVOR et al., 2013; DUBREUIL et al., 2008; SILVA, 2015), and social questions (MUCHAGATA, 2004; SCHMINK et al., 2019; WEIHS; SAYAGO; TOURRAND, 2017). All these studies confirmed the relevance of the pioneer front concept for the understanding and monitoring of the territorial dynamics of Brazilian Amazon.

Few studies have attempted to define the spatial limits of these pioneer fronts, although a number of alternative methodological perspectives have grown out of the increasing availability of spatial data. These data can be used to represent the different stages in the evolution of the pioneer fronts, by combining the classes of land cover and use (ARVOR, 2009; ARVOR et al., 2013), in addition to the formulation of pioneer front typologies on a municipal scale (PACHECO, 2012; RODRIGUES et al., 2009) or by representing them in cells (THALÊS; POCCARD-CHAPUIS, 2014), using annual deforestation rates as indicators.

Clearly, however, the pioneer front is an abstract concept, which is used for the qualitative analysis of complex geographic dynamics, but whose exact spatial limits are difficult to determine,

which hampers cartography and quantitative approaches. In this context, the present study elaborates a diachronic cartography of the pioneer fronts of an Amazon region (the Brazilian state of Pará), which is used as a quantitative analytical model of the deforestation in the region over the past two decades, to provide a spatially explicit explanation of the territorial dynamics of the study area.

MATERIAL AND METHODS

STUDY AREA

The present study focused on the Brazilian state of Pará, which is located in the eastern extreme of Brazilian Amazon, and is divide into 144 municipalities, which are interlinked by either roads or rivers. The state has a total area of 1,245,759 km2, of which, 57% is covered by a mosaic of protected areas (Figure 1), including 30% in conservation units (strictly protected and sustainable use), 25% in indigenous lands, and 2% in military areas (FUNAI, 2018; ICMBIO, 2018; MMA, 2018).

The dynamics of the occupation of the state Pará has included colonization policies and the establishment of access roads that stimulate the movement of pioneers within the region (BECKER, 2004). In the 1960s, the federal government constructed the Belém-Brasília highway (BR-010 federal highway), which runs north-south in the eastern portion of the state, and supported the establishment of the Paragominas development pole. Subsequently, in the 1970s, the Transamazon highway (BR-230 federal highway) extended west across the Tocantins, Xingu, and Tapajós rivers to link the integrated colonization poles of Marabá, Altamira, and Itaituba, respectively. This was followed by the construction of the Cuiabá-Santarém highway (BR-163 federal highway), in the western extreme of the state. These highways provided the backbone for the construction of an expanding network of roads that supported the movements of pioneers, including the PA-150 state highway and BR-155 federal highway in southern Pará, the PA-279 state highway, which links the BR-155 to São Félix do Xingu, and the PA-254 state highway on the left margin of the Amazon River (Figure 1).

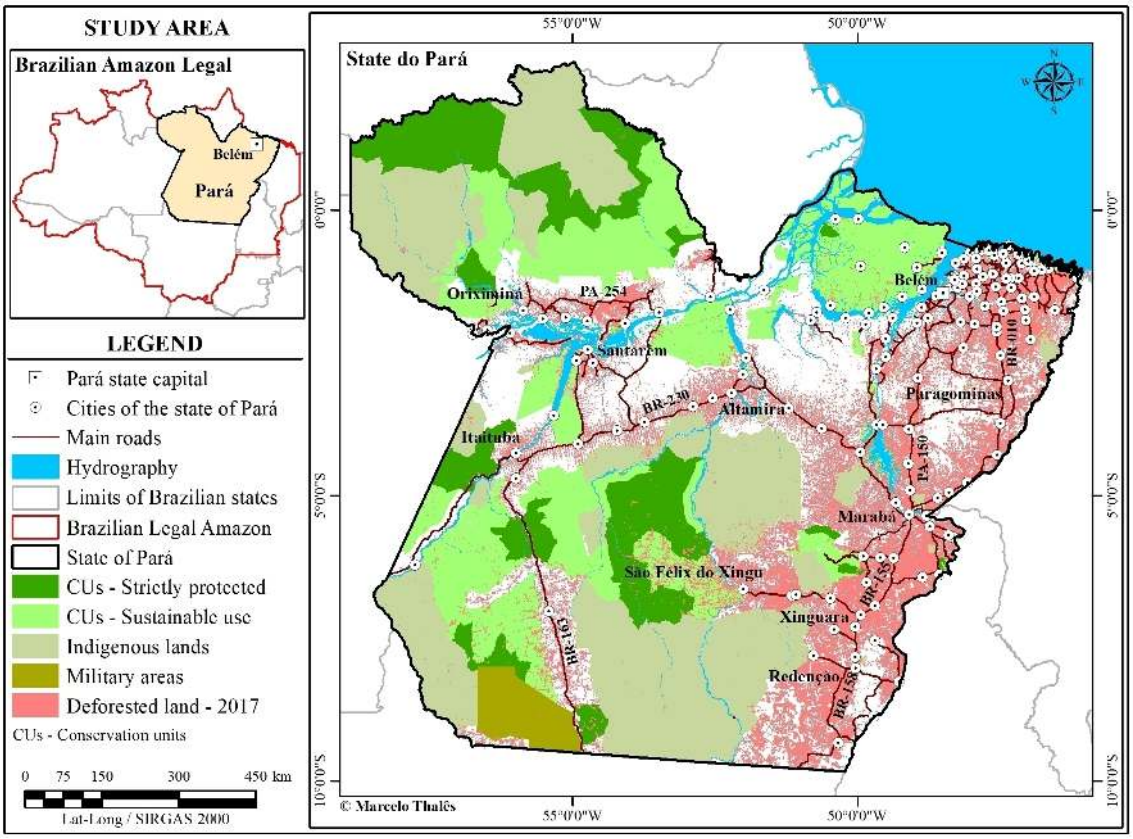

Figure 1 - Location of the study area (source: the author).

These pioneer fronts present distinct patterns of deforestation and development, that have occurred over varying time scales. By 2017, a quarter of the forests of Pará had been converted to other land uses, contributing to the state having the highest deforestation rates in Brazilian Amazon (INPE, 2020). Between 2005 and 2012, there was a major decline in deforestation rates, whose determinants have been described in the scientific literature and government reports, although the subsequent gradual persistence and growth in the deforestation rates, from 2013 onward, that is, the current upward trend in the curve (Figure 2) is yet to be explained adequately.

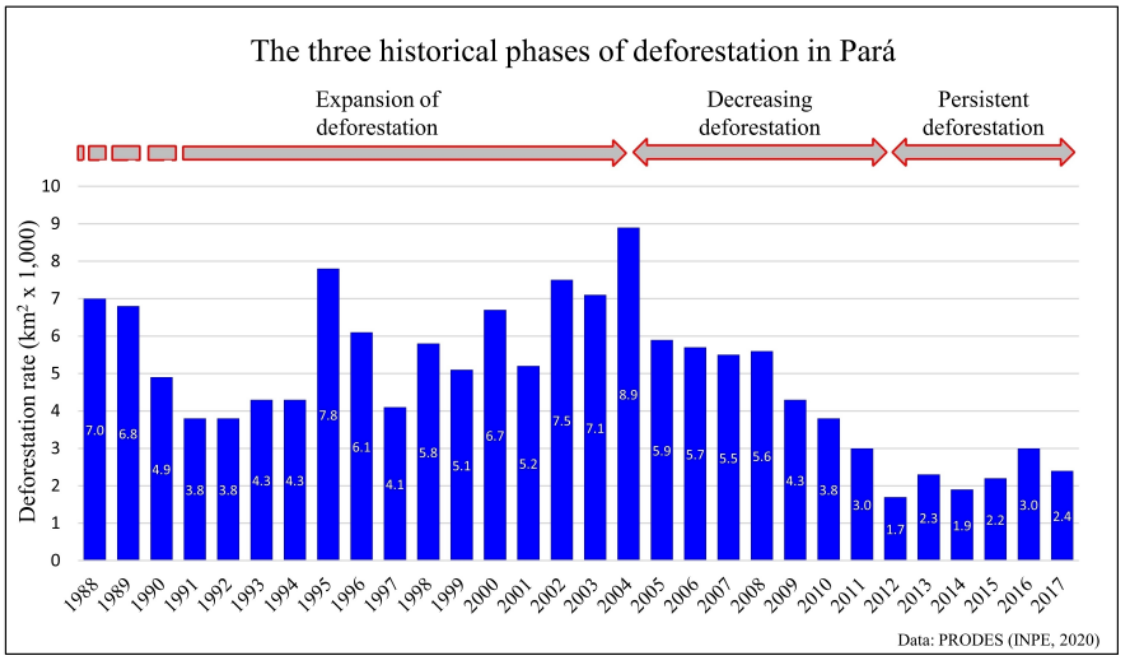

Figure 2 - Evolution of deforestation rates in the Brazilian state of Pará (source: Poccard-Chapuis et al. (2020).

STRUCTURE OF THE DEFORESTATION DATA

DATA from the 2012 and 2017 deforestation, which were provided by the PRODES program, were used to quantify the cumulative deforestation in the state of Pará prior to 2002 and the annual increase between 2003 and 2017 (INPE, 2020). The organization and analysis of these data, and the elaboration of the maps were conducted through a sequence of spatial operations run in the ArcGIS® software. The initial step here was to reclassify the deforestation data from 2017, which were used as the reference for the other analyses, and were available in a raster format with a 30-m spatial resolution, together with the cumulative deforestation classes prior to 2008 and the annual increase for the years between 2009 and 2017. To complement the database for the study period, the deforestation data from 2012 were converted into a raster format and reclassified as the cumulative deforestation up to 2002 and the annual increase in deforestation between 2003 and 2008. Both types of data included the classes forest, hydrography, non-forest, and unobserved areas (cloud cover). The reclassified data were then cropped to the state of Pará and converted into the Albers projection and SIRGAS 2000 datum, with the respective cartographic parameters –central meridian -53º, first and second parallels patterns of 2º and -9º, and latitude of origin of 3º, for the quantification of area.

CARTOGRAPHIC MODEL OF THE PIONEER FRONTS AND DEFORESTATION DYNAMICS

The approach adopted here was based on the conceptual analysis of pioneer fronts of Poccard-Chapuis (2004), derived from Monbeig (1952) and Théry (1976). Poccard-Chapuis (2004)

defines the pioneer front as a portion of land which is transformed from spaces occupied by traditional populations or land available for colonization into a developed region integrated with national social and economic systems. This transition is progressive and, over time, the key factors in the construction of the territory evolve and are consolidated through local development, including property markets, deforestation, public services, and agricultural production and services.

Prior to the beginning of this pioneer dynamic, the territory is in a pre-pioneer phase, whose principal characteristic is the availability of natural resources (forest) and the almost total lack of deforestation, except for some initial activity. The arrival of the pioneer front initiates deforestation and the occupation of the territory, which generates land ownership conflicts in areas with negligible infrastructure and services. As the pioneer movement shifts to the expansion phase and deforestation advances, land ownership becomes better organized, although logistics and urban centers are still precarious. Once the territory has become extensively deforested, a new phase is initiated, in which the model of expansion of the systems of production is converted into a model of diversification and/or intensification, with a well-valued property market and local towns that function as poles of urban services. When it teaches the post-pioneer phase, the original pioneer front becomes similar to the more developed territories from which it originated (POCCARD-CHAPUIS, 2004).

The cartography of the successive phases in the evolution of the pioneer fronts was based on Thalês; Poccard-Chapuis (2014). For this, the territory of the state of Pará was divided into 5 km x 5 km (25 km2) cells, which were cross-referenced with the reclassified deforestation data, excluding the hydrography, non-forest, and unobserved (cloud cover) data. The cumulative percentage of deforestation (PD) was calculated for each cell in relation to the original forest cover for the years between 2002 and 2017.

These percentages of deforestation (PDs) were used to classify the cells in intervals that correspond to the evolutionary phases of the pioneer front (Figure 3). In this classification, a PD of less than 5% is considered to represent the pre-pioneer phase, while a PD of over 90% represents the post-pioneer phase. Between these two extremes, the percentages were divided into three intermediate classes: (i) vanguard (PD = 5–35%); (ii) intermediate (PD = 35–65%), and (iii) rearguard, with a PD of 65–90% (THALÊS; POCCARD-CHAPUIS, 2014).

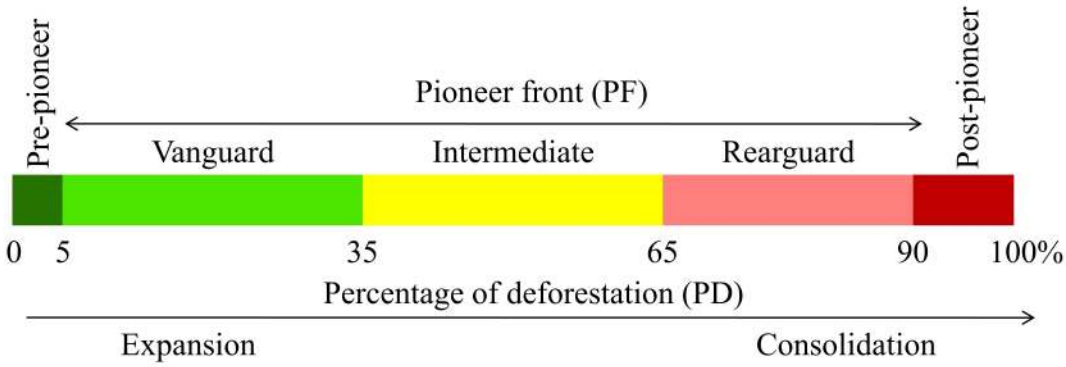

Figure 3 - Cartographic model of the pioneer fronts in the Brazilian state of Pará (adapted from Thalês; Poccard-Chapuis, 2014).

This classification of the cells corresponds to the cartography of the pioneer fronts in 2002 and 2017. The proportion of cells that changed PD class between years provides an understanding of the spatiotemporal dynamic of the period and permits the identification of the regional differences within the territory of the state of Pará, which contributes to the delimitation of the Pioneer Regions (PRs). The term "region" was selected here because the pioneer fronts are already in place, and are advancing in different phases, creating alternative scenarios for which the term "front" is not always appropriate.

In addition to the cartography of the pioneer fronts at the two extremes of the study period, that is, in 2002 and 2017, this approach was also applied to three intermediate years (2004, 2008 and 2012), while the dynamics of the deforestation process is shown for four intervals: 2003–2004, 2005–2008,

2009–2012, and 2013–2017, which were defined based on the observed shifts in deforestation patterns over the whole of this 15-year period. These analyses were used to determine the relationship between deforestation dynamics and the predominant processes in the different classes of pioneer front, their location within the state of Pará, and the degree of deforestation, in an attempt to determine the possible causes of the observed deforestation patterns.

RESULTS

CARTOGRAPHY OF THE PIONEER FRONTS

The cartography of the pioneer fronts at the beginning and end of the study period (2002 and 2017) is shown in Figure 4, providing a visual representation of the deforestation classes in the context of the pioneer march theory formulated by Monbeig (1952) and his disciples. Post-pioneer nuclei can be observed in the more central regions of the state of Pará, surrounded by intermediate and rearguard cells, while in the outlying areas, the cells tend to be in the vanguard class, adjacent to the pre-pioneer cells.

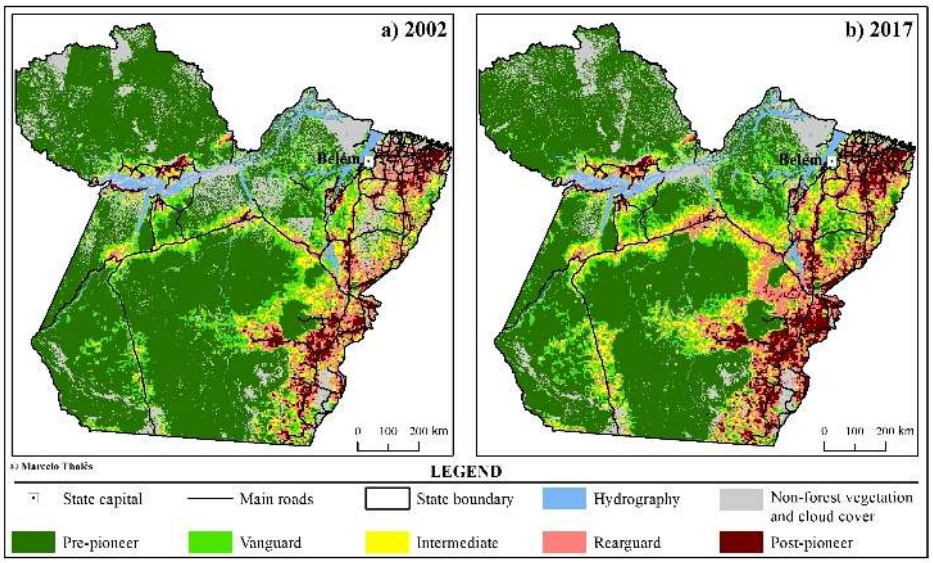

Figure 4 - The pioneer fronts in the Brazilian state of Pará in (a) 2002 and (b) 2017 (source: the author).

Considering the percentage of cells in each deforestation class, between 2002 and 2017, it is clear that the pre-pioneer class decreased from 66% to 58%, which reflects a marked advance on the pioneer movement, which affected areas that were free of deforestation prior to the study period. During the same period, the post-pioneer cells increased from 5% to 8%, indicating an increase in the areas that had advanced beyond the pioneer process of occupation. In the intermediate classes, which represent the pioneer front per se, the vanguard class remained virtually stable, going from 12% to 13%, whereas the intermediate and rearguard classes both increased, from 9% and 8%, respectively, in 2002, to 11% by 2017.

These values do not reflect the full heterogeneity of the changes that occurred in the territory over the study period (Figure 4). To better demonstrate this diversity, and the dynamics of the pioneer fronts in general, it is necessary to verify which cells changed class during this period, in comparison with those that remained unchanged.

DELIMITATION OF THE PIONEER REGIONS

By overlaying the maps of the pioneer fronts of 2002 and 2017, it was possible to provide a simplified overview of the dynamics of the pioneer fronts, and to identify and delimit 10 pioneer regions (PRs). To delimit these regions in a less subjective manner, a selection of the cells that compose each PR

was identified, based on the scientific and the input of specialists in territorial dynamics (Figure 5).

The orthogonal spatial cropping simplified the regional geography, while also permitting the identification of the regional contrasts among the pioneer fronts. Alternative approaches may have been adopted here, such as the application of administrative boundaries, although this would have hampered the interpretation of the data, given that, in some cases, these boundaries overlap two or more PRs.

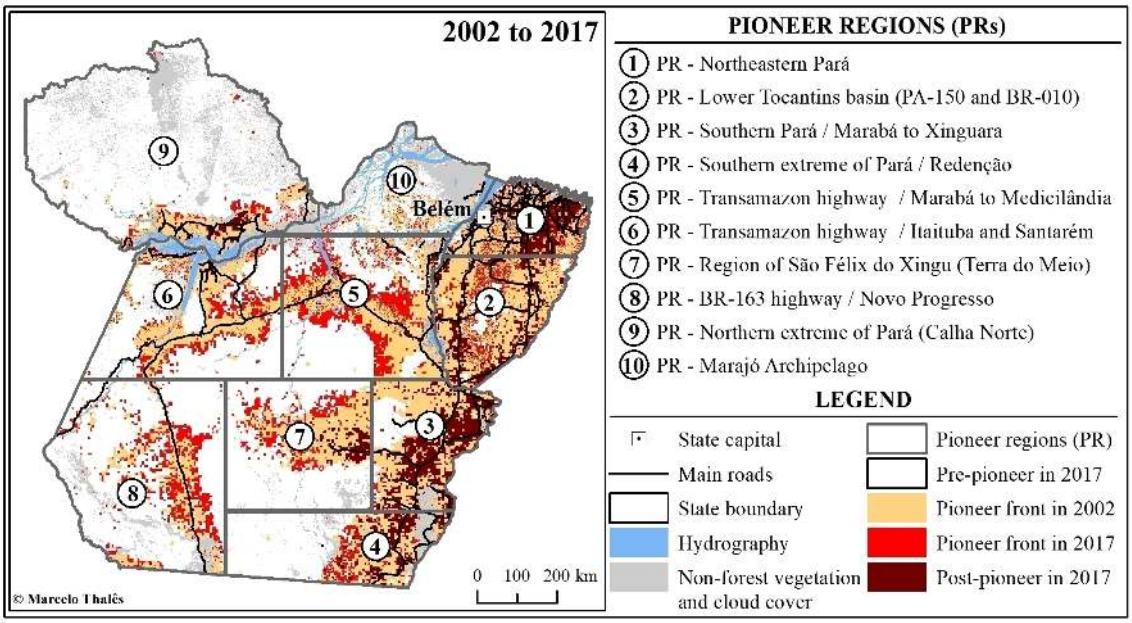

Figure 5 - Dynamics of the pioneer fronts between 2002 and 2017 and the pioneer regions in the Brazilian state of Pará (source: the author).

Pioneer regions 1–4 encompass the whole of the eastern extreme of Pará, which was the first part of the state to be colonized. Northeastern Pará (PR 1) was the first region to be colonized, and is now the most densely populated, and has the best infrastructure and services. Adjacent, to the south, PR 2 includes the lower Tocantins basin, the PA-150 and BR-010 highways, and the Paragominas and Tailândia development poles. Pioneer region 3 lies further south, from Marabá to the pole of Xinguara, while PR 4 corresponds to the extreme south, and the pole of Redenção.

Pioneer regions 5 and 6 are located along the BR-230 federal highway, with PR 5 between the towns of Marabá and Medicilândia, and PR 6 further west, from Medicilândia to Itaituba, including the Santarém sector (northern extreme of the BR-163 federal highway). Pioneer region 7 is the region of São Félix do Xingu, while PR 8 includes the pole of Novo Progresso, on the BR-163 federal highway, in southwestern Pará. Pioneer regions 9 and 10 are located in the northern extreme of the state, with PR 9 in the Calha Norte (North Channel), on the left margin of the Amazon River, and PR 10 being formed by the Marajó Archipelago.

THE DYNAMICS OF THE PIONEER FRONTS IN THE PIONEER REGIONS

Figure 6 shows the percentage of cells that changed class in the cartography of the pioneer fronts between 2002 and 2017, in each pioneer region (PR). The negative values refer to the classes in which the number of cells decreased, and the positive values to the classes in which the number of cells increased, thus providing an overview of the dynamics of the pioneer fronts.

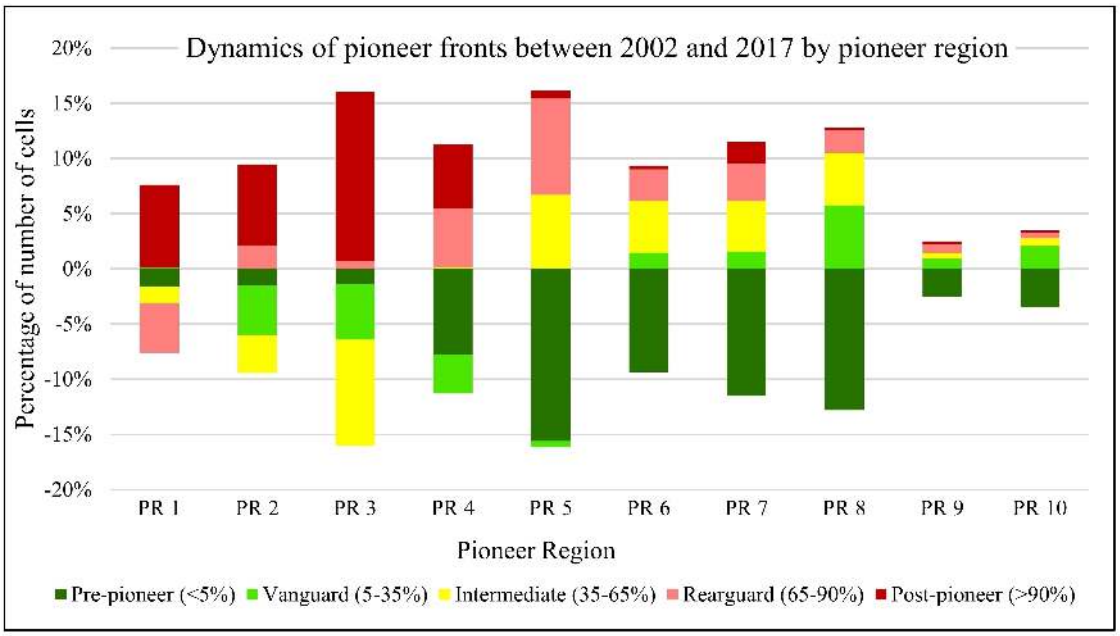

Figure 6 – Dynamics of pioneer fronts from 2002 to 2017 and the ten pioneer regions (source: the author).

Pioneer region 1 underwent little change overall, except for cells that shifted from the rearguard class to the post-pioneer class. This is typical of the final phase of the pioneer movement, that is, when the territory exits the pioneer dynamic and enters the development phase, integrated with the rest of the country.

The maturation of the pioneer process is less advanced in PRs 2 and 3, with an increase in the post-pioneer and rearguard classes, and a decrease in the vanguard and intermediate classes, a pattern that was most accentuated in PR 3. The amplitude of the changes in these regions indicates the occurrence of deforestation, albeit with only a limited advance on the pioneer front.

The pattern was somewhat different in PR 4, with a process of maturation similar to that of PRs 2 and 3, with positive trends in the rearguard and post-pioneer classes, but with losses in the vanguard and, in particular, the pre-pioneer classes, which indicate an advance on the pioneer front. That is, a mixed process, combining maturation with an advance on the pioneer front.

Pioneer region 5 was the most dynamic, typical of an active pioneer front, in which the bulk of the changes in class were due to deforestation, as observed in the percentage loss of cells in the pre-pioneer class. By contrast, there was an increase in the number of cells in the intermediate and rearguard, as well as slight increase in the post-pioneer class.

Pioneer regions 6 and 7 presented scenarios similar to that of PR 5, which was typical of a recently-established and active pioneer front, although the shifts in classes were less dynamic. Pioneer region 7 presented a greater increase in the post-pioneer class.

Pioneer region 8 also had a profile typical of a new and active pioneer front, advancing rapidly into areas of forest not previously affected by the pioneer movement. This evolution of this region was less advanced, however, and the territorial construction is still in its initial phases, with expansion primarily in the vanguard and intermediate classes.

Pioneer regions 9 and 10 were relatively more stable than the other regions, with few cells that changed class during the study period, which is characteristic of an immobilized pioneer movement, with much lower levels of deforestations due to the relative isolation of the region from highways and the principal concentrations of the pioneer movement.

Even so, these pioneer fronts did advance, as indicated by the loss of pre-pioneer cells and the increase in the number of cells in the vanguard, intermediate, and rearguard classes.

THE DYNAMICS AND DISTRIBUTION OF DEFORESTATION ON THE PIONEER FRONTS

The approach adopted in the present study also permitted the analysis of the deforestation dynamics of the pioneer regions and their location in the context of the cartography of the pioneer fronts compiled during the study period.

THE DYNAMICS OF DEFORESTATION

The mean annual deforestation in each of the 10 PRs during the periods 2003–2004, 2005–2008, 2009–2012 and 2013–2017 is shown in Figure 7. In general, it is clear that deforestation rates considerably, both in each PR and among PRs. In particular, PR 5 had the highest deforestation values of any of the 10 regions, while PRs 9 and 10 had the lowest values and were virtually stable over the course of the study period.

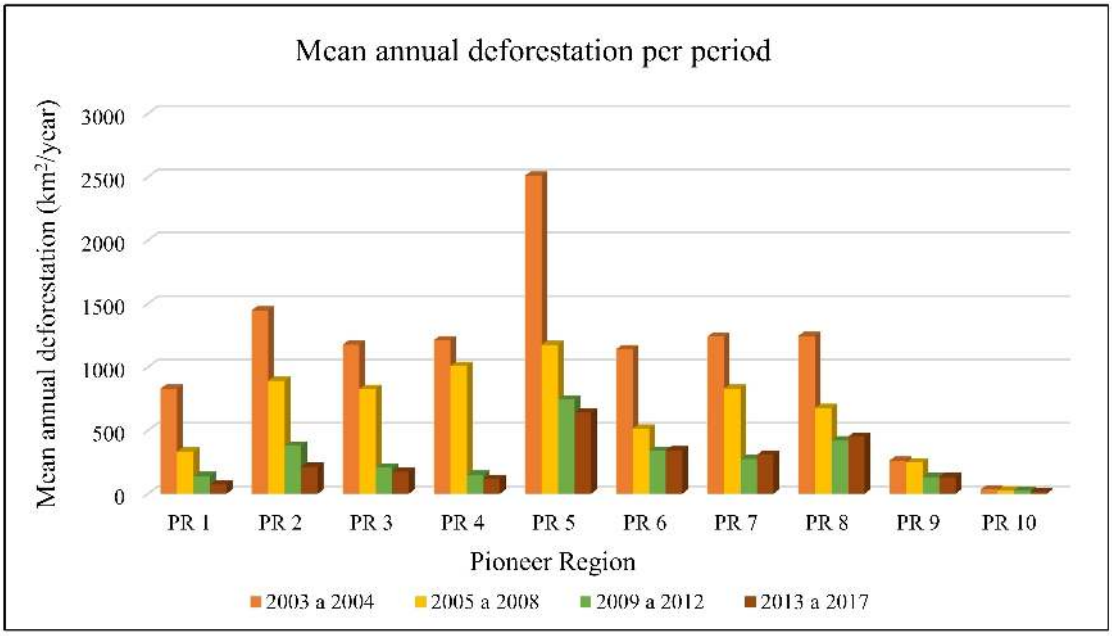

Figure 7 – Deforestation per periods on the pioneer regions of the Brazilian state of Pará (source: the author).

During the initial period (2003–2004), deforestation was relatively high and well distributed among PRs 1–8, while these rates remained high during the subsequent period (2005–2008) in PRs 2–5 and 7. More recently (in 2009–2012 and 2013–2017) deforestation declined substantially, albeit with varying intensities among the different regions, but similar patterns being observed within each region. Deforestation decreased in PRs 2–4 to levels similar to those observed in PR 1, whereas PRs 5 and 7 sustained high deforestation, together with PRs 6 and 8. Persistent deforestation, which occurred after 2013, was more localized, occurring basically in PRs 5–8, whereas it was much lower in the other pioneer regions.

DISTRIBUTION OF THE DEFORESTATION ON THE PIONEER FRONTS

Deforestation decreased in the pre-pioneer and vanguard classes in PRs 1–4, with the clearest decline in this trend being recorded during the two later periods, when deforestation tended to be concentrated in the intermediate and rearguard classes. This pattern indicates that the deforestation is sustained in the more integrated areas, adjacent to the highways and urban centers.

The pattern was clearly different in PRs 5–8, with the pioneer fronts advancing into areas of forest

between 2002 and 2008, as indicated by the proportions of deforestation in the pre-pioneer and vanguard classes. This trend was more subdued between 2009 and 2012, when there was practically no deforestation in the pre-pioneer class, with the exception of PR 8, although this activity did increase in the more recent period. This indicates that the pioneer process was reinitiated during the later period, albeit in much smaller proportions than prior to 2008. Pioneer region 9 followed the same general trend, but over much smaller areas.

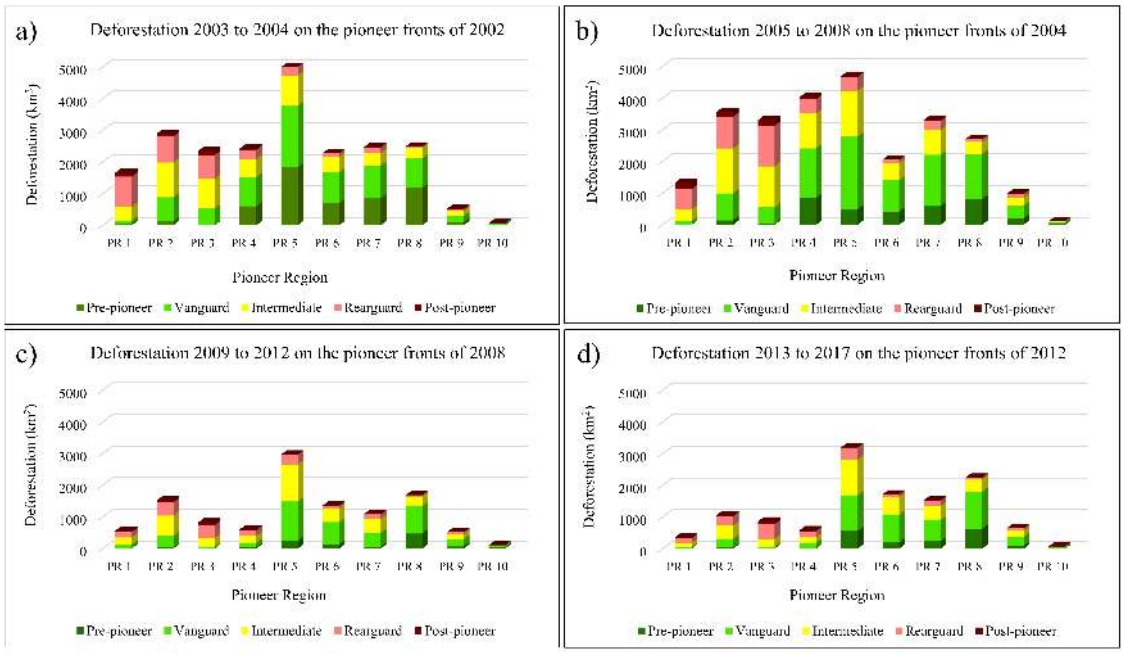

Figure 8 – Deforestation polygons on the pioneer fronts: (a) deforestation in 2003 and 2004 on the pioneer fronts of 2002; (b) deforestation in 2005–2008 on the pioneer fronts of 2004; (c) deforestation in 2009–2012 on the pioneer fronts of 2008; (d) deforestation in 2013–2017 on the pioneer fronts of 2012 (source: the author).

This analysis allowed for the assessment of major patterns, which could be associated with the scenario observed in each pioneer region. In some cases, the pioneer regions shifted pattern, for example, in PR 4, in which there was a clear advance in the pioneer front between 2002 and 2008, when the vast majority of the deforestation occurred in the pioneer and vanguard classes, whereas after 2013, this advance was halted, as observed in the neighboring regions in eastern Pará, with controlled and persistent deforestation, primarily in the rearguard class. Pioneer region 3 also changed over time, shifting from an intermediate process in the initial periods to one of consolidation during the later periods, together with PR 1.

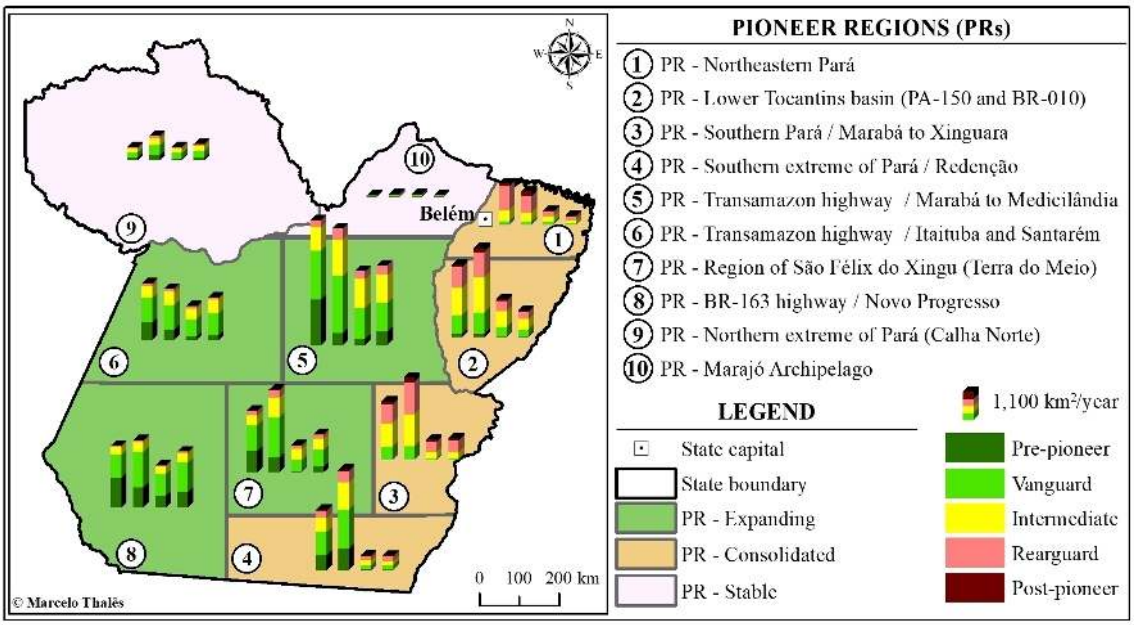

Figure 9 – Spatial distribution of the pioneer regions and deforestation on the pioneer fronts in the Brazilian state of Pará (source: the author).

DISCUSSION

The analytical approach adopted in the present study permitted the cartographic construction of the different phases of the evolution of the pioneer fronts, which was divided into five classes, used to analyze the spatiotemporal dynamics of the process. A total of 10 pioneer regions (PRs) were identified in the state of Pará, and these regions were associated with three major trends of deforestation – expansion, stabilization, and consolidation. The use of the orthogonal boundaries helped to overcome the difficulties of delimiting the different PRs with adequate precision, and allowed them to be analyzed individually and compared systematically. Other potential analytical options, such as the municipal boundaries could be considered in the same approach, or even as a complement to this approach, where the objective of the study is the provision of guidelines for local governance.

The association of the deforestation dynamics with the cartography of the pioneer fronts contributed to the visualization of regional contrasts and the identification of the PRs that are free of deforestation, either through the lack of available forest or because it has been possible to save the existing forest, the PRs in which deforestation was concentrated in the initial phases of the pioneer front (more extensive use), and those that were nearing the post-pioneer phase (more intensive use). It was also possible to observe shifts in the pattern observed in a given region in comparison with the initial years of the study period, when the deforestation was more intense, in general, provoking changes in the spatial structure of the pioneer front in more recent years, in particular from 2008 onward, when deforestation was less intense overall.

The analytical approach adopted in the present study provided an improved interpretation of the causes of the deforestation, with emphasis on three principal scenarios:

(i) territories for the intensification of farming: deforestation persists in the intermediate and rearguard classes, in which property prices increase, and access to agricultural technology, services, and transport is facilitated, a priori, and the regions is more developed, as predicted by the evolutionary model of the pioneer fronts. In this case, deforestation is linked to the intensification of agricultural practices, which increases the pressure on the forests located on the best located land most adequate for farming (PIKETTY et al., 2015). This tendency is relatively discrete, but well-established, and affects primarily PRs 1–4;

(ii) territories in expansion: deforestation occurs primarily in the pre-pioneer and vanguard

classes, which reflects a tendency for the pioneer front to advance into areas of forest. This process represents a strategy of occupation and property speculation, with the primary aim of appropriating land at low cost, which can then be sold at a profit, rather than (in most cases) the development of agricultural projects. This strategy of deforestation and land speculation has a major impact on the economic and social structure of the territory;

(iii) territories free of deforestation: deforestation is residual and from this perspective, PR 1 is a completely post-pioneer region, while PR 10 is a region in which deforestation is not advancing. While deforestation rates are also reduced in PRs 3, 4, and 9, it is still unclear how these regions will progress in the future.

By providing both qualitative and quantitative perspectives on the evolution of deforestation patterns in the study area, the approach adopted in the present study contributes in a significant way to the debate on the prevention and suppression of deforestation in Brazilian Amazon. In particular, the study provides important insights into the most effective policy options and measures, and how to design and implement these actions in the context of the local mechanisms of deforestation, in addition to contributing to territorial development. Pacheco et al. (2017) emphasized the need for economic incentives and financial support to enable rural producers to adopt a deforestation-free model, but also reinforce the importance of measures of environmental regulation and control. They also consider that public policy should provide incentives, simultaneously, for the adoption of mechanisms of development that involve the smallest possible environmental impact.

CONCLUSION

The annual deforestation is a good indicator for the construction of a cartographic model of the pioneer fronts. This approach has the advantage of using few, freely-available data, which can be analyzed using simple tools and products that can be easily understood. This guarantees transparency for decision-makers and even non-specialists.

The method used here permitted the systematic analysis of the spatiotemporal dynamics of the pioneer movement and the contrasts among the pioneer regions that make up the Brazilian state of Pará, in addition to the classification of the advance of the deforestation on each of the state's pioneer fronts. It was also possible to identify the territories associated with deforestation, where pioneer fronts advance to incorporate new areas or where agricultural practices are intensifying, or even territories that carefree of deforestation.

The specific parameters of the regional dynamics observed in the present study indicate possibilities for the development of effective monitoring tools that can contribute to both the control of deforestation and the development of the territory, articulated through policies adequate to the different administrative spheres, while at the same time, involving the local actors. It is important to note that the causes of the deforestation, as found in the present study, are determined by specific local factors, which emphasizes the need for adequate local knowledge, to support any effective policy-making. It will also be necessary to complement the analyses presented here with new indicators, such as parameters related to patterns of land ownership and transportation infrastructure, for a better understanding of the regional dynamics observed in the present study, and a more comprehensive delimitation of the pioneer regions.

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