"Even if I knew that tomorrow the world would go to pieces, I would still plant my apple tree."

Martin Luther

Universidad de Alcalá

Universidad de Alcalá

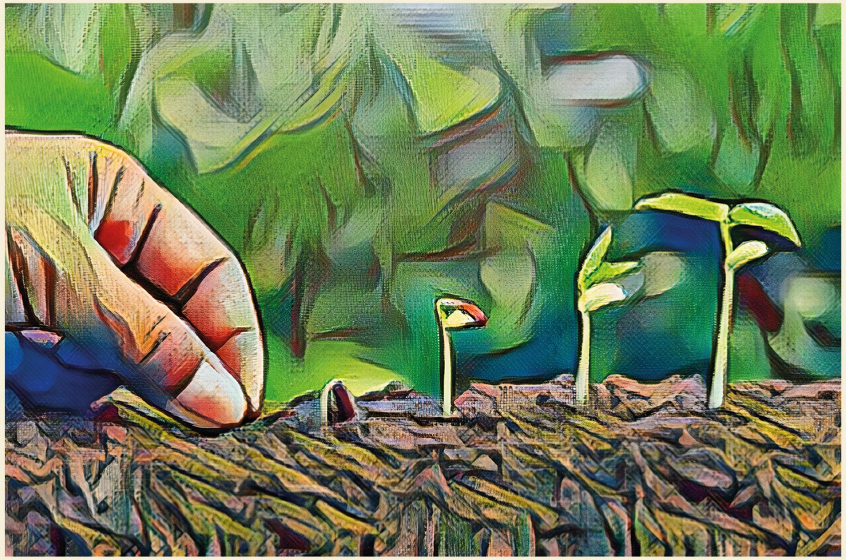
Forest loss and forest restoration in the Brazilian Amazon.
An overview and applied studies in Paragominas (Pará)

2020

Denis Conrado

Forest loss and forest restoration in the Brazilian Amazon

An overview and applied studies in Paragominas (Pará)



Denis Conrado da Cruz

2020

TESIS DOCTORAL

Programa de Doctorado en Ecología, Conservación y Restauración de Ecosistemas

Universidad de Alcalá

Universidad de Alcalá

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José M. Rey Benayas, Catedrático de Ecología de la Universidad de Alcalá y director y tutor de esta Tesis Doctoral, hace constar:

Que el trabajo descrito en la presente memoria, titulado *Forest loss and forest restoration in the Brazilian Amazon. An overview and applied studies in Paragominas (Pará)*, ha sido realizado bajo mi dirección por Denis Conrado da Cruz en la Unidad Docente de Ecología del Departamento de Ciencias de la Vida de la Universidad de Alcalá, dentro del Programa de Doctorado "Ecología, Conservación y Restauración de Ecosistema" (D330), reuniendo todos los requisitos necesarios para su aprobación como Tesis Doctoral.

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Gracialda Costa Ferreira, Profesora Adjunta del Instituto de Ciencias Agracias de la Universidad Federal Rural de la Amazónia y codirectora de esta Tesis Doctoral,

hace constar:

que el trabajo descrito en la presente memoria, titulado "Forest loss and forest restoration in the Brazilian Amazon. An overview and applied studies in Paragominas (Pará)", ha sido realizado bajo mi dirección por Denis Conrado da Cruz en la Unidad Docente de Ecología del Departamento de Ciencias de la Vida de la Universidad de Alcalá, dentro del Programa de Doctorado "Ecología, Conservación y Restauración de Ecosistema" (D330), reuniendo todos los requisitos necesarios para su aprobación como Tesis Doctoral.

Belém, 21 de junio de 2020.

Gracialda Costa Ferreira

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HAGO CONSTAR que la Tesis Doctoral titulada "Forest loss and forest restoration in the Brazilian Amazon. An overview and applied studies in Paragominas (Pará)", presentada por D/Dª Denis Conrado da Cruz, bajo la dirección del / de la Dr/a. José María Rey Benayas, Gracialda Costa Ferreira, ha sido realizada por compendio de artículos, reuniendo los requisitos exigidos a este tipo de tesis, así como los requisitos científicos de originalidad y rigor metodológicos para ser defendida ante un tribunal. Esta Comisión ha tenido también en cuenta la evaluación positiva anual del doctorando, habiendo obtenido las correspondientes competencias establecidas en el Programa.

Para que así conste a los efectos del depósito de la tesis, se firma en Alcalá de Henares a 30 de Junio de 2020

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Universidad de Alcalá

Forest loss and forest restoration in the Brazilian Amazon. An overview and applied studies in Paragominas (Pará)

Ph.D. Thesis

Denis Conrado da Cruz

Thesis supervisors

José María Rey Benayas
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Julio 2020

Programa de Doctorado en Ecología, Conservación y Restauración de Ecosistemas

Aquele garotinho que não pôde estudar, que aos 6 anos já acompanhava seu pai a pescar, que não podia brincar, que passava horas no mato a caçar, que não podia jantar, que levantava as 4 da manhã para plantar e que nunca pôde sonhar, a você meu pai. Aquela menininha que não podia pensar, que tão jovenzinha só deveria as louças lavar, que ainda criança já deveria cozinhar, que com suas amiguinhas não podia nem falar, que seus irmãozinhos deveria cuidar, que muito jovem já deveria casar e que nunca pode estudar, a você minha mãe.

CONTENT

ABSTRACT / RESUMEN

ABSTRACT

The Brazilian Amazon has the largest tropical forest that holds the greatest biodiversity in the world. There is a strong link between the country's economic development and the exploitation of its natural resources, which have resulted in a significant forest and biodiversity loss. The general objective of this Thesis was to evaluate the potential for forest restoration to enhance biodiversity and ecosystem services in the Brazilian Amazon. The Thesis has originated four scientific publications. The first one provides an overview of forest loss, on one side, and projects, techniques, and publications on the recovery of degraded areas in the region, on the other side. After the loss of one fifth of the original forest extent, there has been an attempt to halt deforestation in the Brazilian Amazon. We identified 405 restoration projects, but we noticed a small number of high-quality scientific publications. The second publication evaluates vulnerability to soil erosion. The studied municipality (Paragominas) has a low soil vulnerability in its most part (77%), and only 3% of it was estimated as of high soil vulnerability. The third publication evaluates the outcomes of two contrasting forest restoration techniques by monitoring indicators in post-mining areas. Both techniques provided good recovery outcomes, although some indicators attained higher levels than others. The fourth publication assess tree composition, functional types, effect of distance between restored sites and seed sources, and the conservation status of established tree species under different forest restoration techniques (namely seedling planting, natural regeneration, and nucleation) implemented in post-mining sites. A substantial amount of tree biodiversity was recovered in these sites, but the techniques differed in specific outcomes. In short, our results are in agreement with the starting hypothesis that the Brazilian Amazon has undergone severe deforestation and, concomitantly, offers outstanding opportunities for forest restoration that will enhance biodiversity and provide benefits to humans.

RESUMEN

La Amazonía brasileña tiene el bosque tropical más extenso y con mayor biodiversidad del mundo. Existe un fuerte vínculo entre el desarrollo económico del país y la explotación de sus recursos naturales, que resultó en pérdidas significativas de bosque y biodiversidad. El objetivo general de esta Tesis fue evaluar el potencial de la restauración forestal para aumentar la biodiversidad y los servicios ecosistémicos en la Amazonía brasileña. Los resultados han originado cuatro publicaciones científicas. La primera proporciona una revisión general de la deforestación y de los proyectos, técnicas y publicaciones sobre la recuperación de las áreas degradas en la región. Con un quinto del bosque original desaparecido, ha habido un intento de frenar la deforestación en la Amazonía brasileña. Identificamos 405 proyectos de restauración, pero un número reducido de publicaciones científicas de calidad elevada. La segunda publicación evalúa la vulnerabilidad a la erosión del suelo. El municipio estudiado (Paragominas) tiene un 77% de su extensión con baja vulnerabilidad a la erosión y solo un 3% con elevada vulnerabilidad. La tercera publicación evalúa el desempeño de las técnicas de restauración forestal mediante el monitoreo de indicadores en áreas de explotación minera. Las técnicas evaluadas fueron eficaces para recuperar estas zonas, aunque algunos indicadores alcanzaron mayores niveles que otros. La cuarta publicación analiza la composición arbórea, tipos funcionales, efecto de la distancia entre los sitios restaurados y las fuentes de semillas y el estado de conservación de las especies establecidas en áreas restauradas post minería, mediante técnicas de plantación, regeneración natural y nucleación. Una cantidad sustancial de biodiversidad arbórea se recuperó en estas zonas, pero las tres técnicas difirieron en los resultados específicos. En síntesis, los resultados confirman la hipótesis de partida de que la Amazonía brasileña ha sufrido una deforestación severa y, simultáneamente, ofrece grandes oportunidades para la restauración forestal que incrementará la biodiversidad y ofrecerá beneficios a los humanos.

EXTENDED ABSTRACT

Tropical forests, despite occupying only 7% of the Earth's surface, harbor more species of animals and plants than all the other biomes on the planet combined. The Brazilian Amazon has one-third of these forests. On top of biodiversity conservation, the region is important for global climate regulation. Due to its economic relevance and government incentives for development, the Brazilian Amazon was invaded and irrationally exploited for many years, which caused a significant decrease in its forest area and an irreversible biodiversity loss. In this context, we propose as a general objective of this Thesis to evaluate the potential of forest restoration to increase biodiversity and ecosystem services in the Brazilian Amazon. To achieve this goal, four specific objectives are proposed, which related results have originated four scientific publications. In addition to these four chapter-articles, the Thesis presents a General introduction and a Conclusions chapter.

Chapter 2, published in *New Forests*, is a general and systematic review of deforestation in the historical and political context of the Brazilian Amazon. The region was intensively deforested as from 1975, mainly due to the government's promotion of agricultural activities, which resulted in a net deforestation of 760.654 km² from the 1975-2018 period. In the last few decades, due to joint actions by governmental and non-governmental organizations as well as national and international research institutions, deforestation in the Brazilian Amazon has decreased (for example, 5,375 km² or 5.2% from 2008 to 2018). Through a systematic search, we have compiled 405 forest restoration projects since 1950. However, it was not possible to estimate the recovered area or the efficiency of such restoration projects due to the absence of published results. In general, these projects do not conform to local specificities as they do not comply with the restoration standards and protocols established by government agencies and/or qualified professionals and, in many cases, are based on exotic species. There is a lack of quality scientific production on forest restoration in the region, since only 152 scientific articles were identified, of which 29% were published in international journals.

Chapter 3, published in *Geographia Technica*, assesses vulnerability to soil erosion in Paragominas, a municipality in Para state. From five attributes related to geology, slope, soil, land use, and climate, evaluated by two GIS techniques based on the RUSLE and Ecodynamic concept, we identified that a large part of the municipality (77% or 60% according to the first or the second technique) has good soil structure, while only 3% of the land was considered as highly vulnerable. With only 55 years since its foundation, Paragominas presents 45% of deforested territory. Analyses of land use practices, which are correlated with

economic data, showed intense agricultural activity, logging, and mining, which resulted in serious environmental damage.

Chapter 4, published in *Floram*, evaluates the performance of forest restoration techniques by monitoring indicators in mining areas. The results of seedling planting and natural regeneration in 92 ha were evaluated by analyzing the following indicators: (1) degree of tree cover; (2) presence of natural regeneration; (3) presence of erosion; (4) forest leaf litter; (5) density of plants; (6) diversity; (7) average height; (8) basal area; (9) mortality; (10) increase in diameter; (11) presence of exotic species; (12) presence of endangered species [5-12 for trees]; and (13) presence of traces of fauna return. Both techniques provided good recovery results for the post-mining areas. Natural regeneration, in general, showed better performance for the density of plants and presence of exotic species, while seedling planting was better for the diversity of species and fauna presence.

Chapter 5, published in *Forests*, discusses tree composition, functional types, the effect of distance between restored sites and seed sources and the conservation status of established species in restored areas of bauxite extraction through proven restoration techniques (seedling planting, natural regeneration, and nucleation). There is a substantial amount of tree diversity that is recovered in areas of post-mining activities, with 119 species identified in just 3 ha of sampled area. The three techniques differed in terms of tree composition, abundance, richness, species diversity, and successional groups. Instead, the techniques were similar for dispersal and pollination syndromes, with most species having entomophilous pollination and zoochoric dispersal. Species abundance and richness were negatively correlated with distance between the restored sites and the seed sources. There was a sharp decrease in species abundance and richness down to 250 m from seed sources at sites restored through natural regeneration and nucleation.

In summary, the results confirm the starting hypothesis that the Brazilian Amazon has suffered severe deforestation and, simultaneously, offers great opportunities for forest restoration that will increase biodiversity and offer benefits to humans, as it is the regulation of soil erosion. However, the attitude of the current Bolsonaro's government, in an attempt to improve the country's economy, is encouraging various land use activities without due responsibility. Based on the analysis of the field data, it is concluded that the combination of different forest restoration strategies in mining sites resulted in remarkable levels of tree diversity recovery. On the other hand, we emphasize that each restoration technique must be adapted to the local context with a defined objective in order to achieve the expected outcomes. The present study can help decision-making regarding the restoration of the Amazon rain forest.

RESUMEN EXTENDIDO

Los bosques tropicales, a pesar de ocupar solo el 7% de la superficie terrestre, albergan más especies de animales y plantas que todos los demás biomas del planeta juntos. La Amazonía brasileña tiene un tercio de todos estos bosques. Además de para la conservación de la biodiversidad, la región es importante para la regulación del clima global. Debido a su relevancia económica e incentivos gubernamentales para el desarrollo, la Amazonía brasileña fue invadida y explotada irracionalmente durante muchos años, lo que provocó una disminución significativa de su superficie forestal y pérdidas irreversibles de biodiversidad. En este contexto, planteamos como objetivo general de esta Tesis evaluar el potencial de la restauración forestal para aumentar la biodiversidad y los servicios ecosistémicos en la Amazonía brasileña. Para alcanzar este objetivo, se proponen cuatro objetivos específicos cuyos resultados relacionados han originado cuatro publicaciones científicas. Además de estos cuatro capítulos-artículos, la Tesis presenta una Introducción general y un capítulo con las Conclusiones más relevantes.

El Capítulo 2, publicado en *New Forests*, es una revisión general y sistemática de la deforestación en el contexto histórico-político de la Amazonía brasileña. La región fue intensamente deforestada a partir de 1975, principalmente debido al fomento por parte del gobierno de las actividades agropecuarias, lo que resultó en una deforestación neta de 760.654 km² en el periodo 1975-2018. En las últimas décadas, debido a acciones conjuntas de organizaciones gubernamentales, no gubernamentales e instituciones de investigación nacionales e internacionales, la deforestación de la Amazonía brasileña se ha reducido (por ejemplo, 5.375 km² o 5,2% en el periodo de 2008 a 2018). Mediante una búsqueda sistemática, hemos compilado 405 proyectos de restauración forestal implementados desde 1950. Sin embargo, no fue posible estimar la cantidad de área recuperada o la eficiencia de estos proyectos de restauración debido a la ausencia de resultados publicados. En general, los proyectos no se ajustan a las especificidades locales, no cumplen con los estándares y protocolos de restauración establecidos por agencias gubernamentales y/o profesionales cualificados y, en numerosos casos, se basaron en especies exóticas. Falta producción científica de calidad sobre la restauración forestal en la región, ya que solo se identificaron 152 artículos científicos de los cuales apenas el 29% se publicaron en revistas internacionales.

El Capítulo 3, publicado en *Geographia Technica*, evalúa la vulnerabilidad a la erosión del suelo en Paragominas, un municipio del estado de Pará. A partir de cinco atributos relacionados con la geología, pendiente, suelo, uso del suelo y clima, evaluados mediante dos técnicas GIS basadas en la RUSLE y el Concepto ecodinámico, identificamos que gran parte del municipio (77% o 60% según la primera o la segunda técnica) tiene una buena estructura del suelo, mientras que sólo un 3% de la superficie se estimó como de una alta vulnerabilidad. Con tan solo 55 años desde de su fundación, Paragominas presenta un 45% de su territorio deforestado. Los análisis de las prácticas de uso del suelo, que están correlacionadas con los datos económicos, mostraron una intensa actividad agrícola, tala y minería, que resultaron en graves daños ambientales.

El Capítulo 4, publicado en *Floram*, evalúa el desempeño de las técnicas de restauración forestal mediante el monitoreo de indicadores en áreas de explotación minera. Se evaluaron los resultados de las técnicas de plantación de árboles y la regeneración natural en 92 ha mediante el análisis de los siguiente indicadores: (1) grado de cobertura arbórea; (2) presencia de regeneración natural; (3) presencia de erosión; (4) hojarasca; (5) densidad de plantas; (6) diversidad; (7) altura media; (8) área basal; (9) mortalidad; (10) incremento de diámetro; (11) presencia de especies exóticas; (12) presencia de especies amenazadas de extinción [5-12 para árboles]; y (13) presencia de rastros de fauna. Ambas técnicas proporcionaron buenos resultados de recuperación de las áreas después de la extracción minera. La regeneración natural, en general, mostró mejores resultados para los indicadores de densidad de plantas y presencia de especies exóticas, mientras que la plantación fue mejor para la diversidad de árboles y presencia de fauna.

El Capítulo 5, publicado en *Forests*, analiza la composición de árboles, los tipos funcionales, el efecto de la distancia entre los sitios restaurados y las fuentes de semillas, y el estado de conservación de las especies establecidas en áreas restauradas de una explotación de bauxita mediante técnicas de restauración contrastadas (plantación, regeneración natural y nucleación). Existe una cantidad sustancial de diversidad de árboles en áreas recuperadas después de las actividades mineras, identificándose 119 especies en solo 3 ha de superficie muestreada. Los resultados de las diferentes técnicas de restauración se diferenciaron en términos de composición de árboles, abundancia, riqueza, diversidad de especies y grupo sucesional. En cambio, las técnicas se parecieron en los síndromes de dispersión y polinización dominantes, teniendo la mayoría de las especies polinización entomofílica y dispersión zoocórica. La abundancia y la riqueza de especies se correlacionaron de forma negativa con la distancia entre los sitios restaurados y las fuentes de semillas. Hubo, además, una fuerte disminución en la abundancia y la riqueza de especies hasta los 250 m de las fuentes de semillas en los sitios restaurados mediante regeneración natural y nucleación.

En síntesis, los resultados confirman la hipótesis de partida de que la Amazonía brasileña ha sufrido una deforestación severa y, simultáneamente, ofrece grandes oportunidades para la restauración forestal que incrementará la biodiversidad

y ofrecerá beneficios a los humanos, como es la regulación de la erosión del suelo. Sin embargo, la actitud del actual gobierno de Bolsonaro, en un intento por mejorar la economía del país, está alentando diversas actividades de uso de la tierra sin la debida responsabilidad. Los resultados del análisis de los datos de campo permiten concluir que la combinación de diferentes estrategias de restauración forestal en sitios de extracción minera proporcionó una recuperación notable de la diversidad de árboles. Por otro lado, se resalta que cada técnica y acción de restauración debe adaptarse al contexto local y tener un objetivo bien definido, con el fin de obtener los resultados esperados. El presente estudio puede ayudar a tomar de decisiones sobre la restauración del bosque tropical amazónico.

1. GENERAL INTRODUCTION

CHAPTER 1

General introduction

This PhD Thesis is an outcome of the international and multidisciplinary project named *Biodiversity, propagation of plant species and restoration of degraded areas from mining bauxite in the southeast region of Pará*. The major goal of this project was to evaluate soil attributes, biodiversity features and plant propagation to develop a model of forest recovery in mined landscapes, concerning ecological and economic efficiency. The Thesis provides an overview of forest loss and forest restoration in the Brazilian Amazon and develops applied case studies related to soil erosion and post-mining restoration in the Paragominas municipality (Pará state). In this chapter, I will provide an introduction that explains the high levels of biodiversity, particularly of tree species, that the region holds, and how this biodiversity is threatened by forest loss and degradation. Next, I will address the question "How to recover Amazonian biodiversity?" to introduce the most relevant forest restoration practices and will justify the selection of the study area. Finally, I will pose the aims and hypotheses of this study and summarize the organization of the Thesis and associated publications that have stemmed from it.

1.1. HIGH BIODIVERSITY LEVELS IN THE BRAZILIAN AMAZON ARE THREATENED

The Brazilian Amazon extends over a territory of approximately 4,196,943 million km^2 (IBGE, 2004), which is greater than the territorial extent of all 27 European Union countries combined (**Figure 1**). The region's hydrographic basin is the largest in the world, corresponding to one fifth of all fresh water on the planet. It covers about 6 million km^2 and has approximately 1,100 tributaries, among which is the Amazon River, flowing into the Atlantic Ocean and launching approximately 175 million liters of water per second (MMA, 2018). It holds an immensity of forests, and its exuberant tree tops can reach more than 80 m in height (Gorgens et al., 2019). The Brazilian Amazon is the largest area in the world with dominance of primary vegetation (Pailler, 2016; Wright et al., 2017).

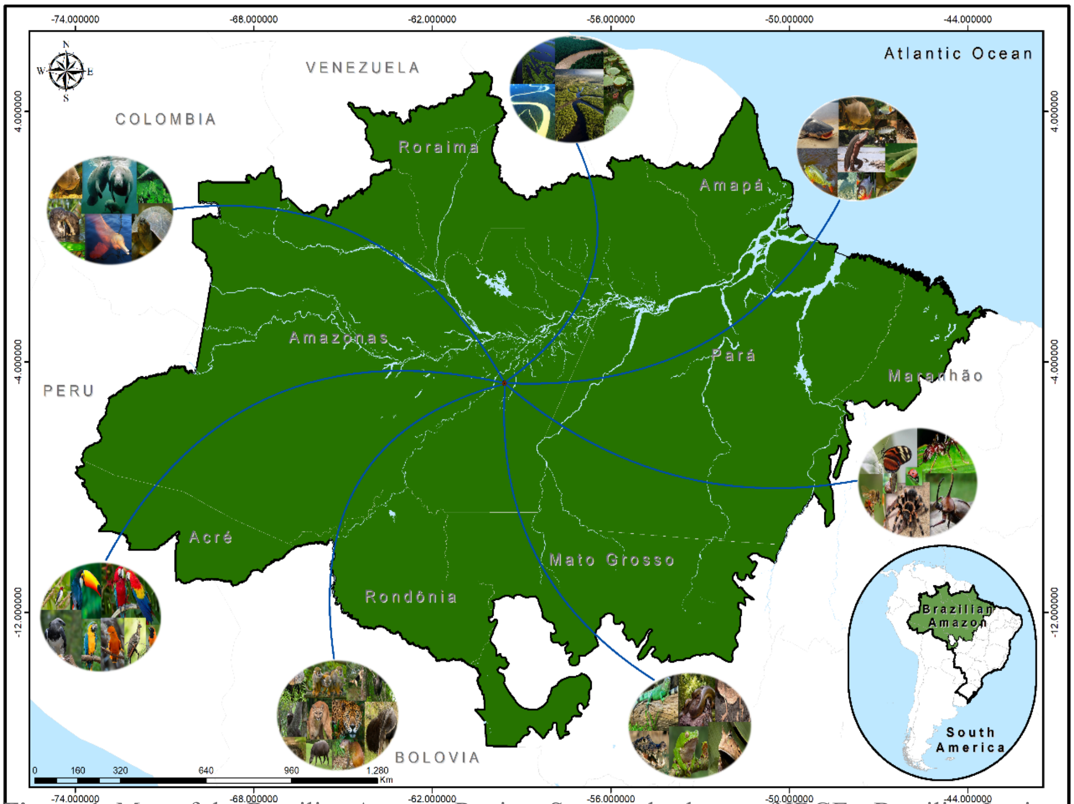

Figure 1. Map of the Brazilian Amazon Region. Source: databases of IBGE - Brazilian Institute of Geography and Statistics, available from https://www.ibge.gov.br/geociencias/informacoes-ambientais/15842-biomas.html, and of CNIG - National Geographic Information Center, available from http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=CAANE.

The number of species on the planet is still unknown; however, from 5 to 10 million eukaryote species have been estimated (May, 2010). The tropical forests contain most of such biodiversity and, according to Barlow et al., (2018), approximately 91% of birds on the planet spend at least part of their life in the tropics. Despite advances in research, one of the biggest gaps in biodiversity concerns the real magnitude of species diversity. There is a huge difference between what has already been described by science and what may actually exist. Such discrepancy was called the "Linnean Shortfall" by Lomolino et al., (2010), who also coined the term used to refer to little knowledge about species distribution as the "Wallacean Shortfall".

Brazil is considered one of the "megadiversity" countries. It is estimated, from all that is known about the different species identified in the world, that between 10 and 15% of them are found in the country. There are more than 100,000 animal species (vertebrates and invertebrates) and 46,000 plant and fungi species (WWF, 2010; Mattos, 2016; Valsecchi et al., 2017). Such megadiversity is due to the Amazon region, which shelters more than half of the known species from tropical forests (May, 2010; Miranda et al., 2012). Thus, it is considered the most biodiverse region on the planet (Ceballos & Ehrlich, 2006; Carvalho & Esposito, 2010; Barbosa et al., 2016). Ca. 40,000 out of the 46,000 plant and fungi species were registered in the Amazon region (Mattos, 2016; Valsecchi et al., 2017; **Figure 2**). Recent studies that report the outstanding levels of the Amazonian tree diversity are those of Wittmann et al., 2006; Stropp et al., 2009; Sakschewski et al., 2016; Cardoso et al., 2017; and Rayol et al., 2019.

There is still much to discover about the Amazonian biodiversity. According to a survey conducted by the WWF, approximately 637 species of plants, 257 of fish, 216 of amphibians, 55 of reptiles, 39 of mammals and 16 of birds were discovered in the Amazon biome from 1999 to 2009 (WWF, 2010). Some 381 more new species in the region were described only from 2014 to 2015, of which 216 are plants, 93 fish, 32 amphibians, 19 reptiles, 20 mammals and one bird (Valsecchi et al., 2017). This biodiversity is the basis for the production of food, beverages, medicines, cosmetics, energy and much of the industrial raw material consumed by humans, which contribute to the high economically strategic value of the region (Ten Kate & Laird, 2019).

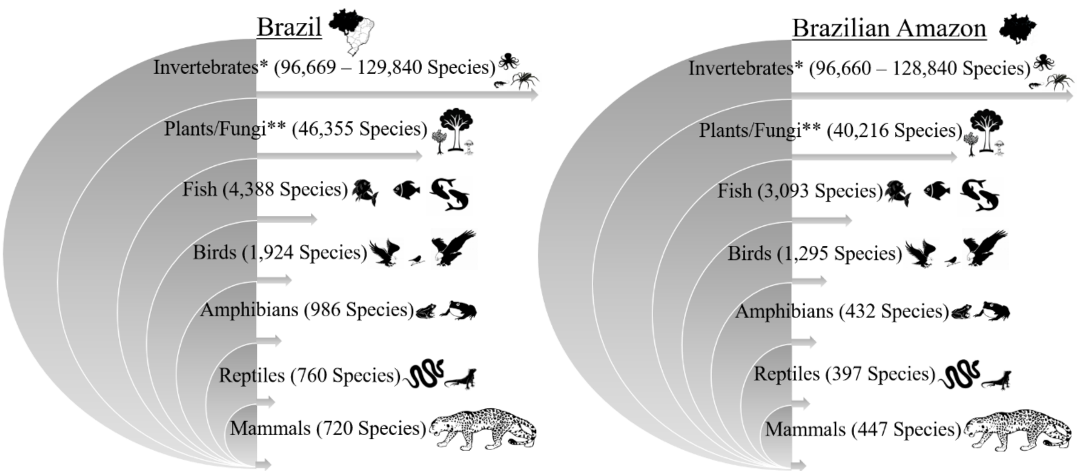

Figure 2. Species recorded for the whole Brazilian territory and the Brazilian Amazon according to major taxonomic groups. Data from MMA - Ministry of the Environment, available from https://www.mma.gov.br/biodiversidade/conservacao-de-especies/fauna-ameacada.html, 5th National Report for the Convention on Biological Biodiversity, available from http://www.terrabrasilis.org.br/ecotecadigital/images/abook/pdf/2017/Marco/Mar.17.39.pdf, and World Wildlife Fund 2010 Report, available from https://www.wwf.org.br/informacoes/bliblioteca/?26345/Amazonia-Viva-uma-decada-de-descobertas-1999-2009; and 2017 Report, available from https://www.wwf.org.br/?60464/Novas-espcies-de--vertebrados-e-plantas--na-Amaznia-2014-2015. *Estimated number of invertebrate species according to Lewinsohn (2005). **Number of species among which the following are plants: 40,629 species - Brazil; 30,216 species - Brazilian Amazon.

Forest loss in Brazilian Amazon

All the greatness of the Amazon does not exempt it from its fragility. Forests live through their own resources, and their balance is extremely susceptible to any interference, whether by anthropic or natural actions, but the changes caused by humans can be irreversible (Hansen et al., 2013; Singh, 2014). There are a number of environmental problems in the region (Liu et al., 2016; Hoeinghaus et al., 2016), caused mainly by uncontrolled use of natural resources over the years. The opening of roads, extraction of wood and ores, urban and industrial growth, fires and, chiefly, deforestation for the expansion of agricultural and livestock frontiers, have been mainly responsible for the current devastation of the Brazilian Amazon (Morris, 2010; Newman et al., 2014; Rodrigues et al., 2015; de Castro Solar et al., 2016; Barlow, 2016).

Before European colonization, the Amazon was occupied by hundreds of indigenous tribes, who extracted resources from the forest only for their subsistence (Dowie, 2011). From the 17th century on, the landscape in the region underwent profound changes that were promoted by the extraction of wood and non-wood products (Batista, 2007; Gradwohl & Greenberg, 2013). In the late 19th century and early 20th century, there was intense exploration of latex from rubber trees (*Hevea brasiliensis*), which brought approximately 500 thousand migrants to the region (Barlow, 1997). The period of greatest degradation in the Brazilian Amazon occurred from the second half of the 20th century on, due to deforestation encouraged by the Brazilian government to colonize and develop the region. It was a period marked by large projects that were installed in the Amazon (Hall, 1991; da Cruz et al., 2020a).

The major projects in the Brazilian Amazon began with the creation of the Amazon Development Plan (PDA) in the 1950s. After that plan was implemented, a military dictatorship was established in the country in the 1960s. The dictatorship wanted the unification of the country; "Integrate so as not to Forfeit" was its slogan (Becker, 2000). In the 1970s, the opening of the Amazon began with the construction of large highways, connecting it to the other regions of the country (Becker, 2001; Serra & Fernández, 2004; Perz et al., 2005). The major projects were: a) Great Carajás Project - *Projeto Grande Carajás* (1979-1986), with the greatest mineral potential on the planet; b) *Polamazônia* - Program for Agricultural and Agribusiness Centers in the Amazon (1979-1985), responsible for the implementation of industrial agricultural exploitation; and c) *Polonoroeste* - Program for the Integrated Development of Northwestern Brazil (1981-1985), responsible for paving BR-364, one of the strategic highways in the colonization actions for the Amazon (Barbosa, 2000; Reid, 2014; Mesquita, 2015).

The result of this historical and political process of economic development is a highly altered Amazon. By 1975, only 0.5% (27.699 km^2) of the Amazon was deforested. But after 10 years of operation of the major projects mentioned above, approximately 7% (352,096 km^2) of the territory had been devastated (an increase of 1,171% in deforestation), and, in 2018, approximately 20% (788,535 km^2) of the region had already been deforested and converted into other uses (**Figure 3;** da Cruz et al., 2020a). The regions of maximum deforestation in the Amazon were along the southern and eastern edges, an area known as the “Arc of Deforestation”, which were and still are strategic regions for expansion of agriculture and livestock (Vieira et al., 2008; Costa & Pires, 2010).

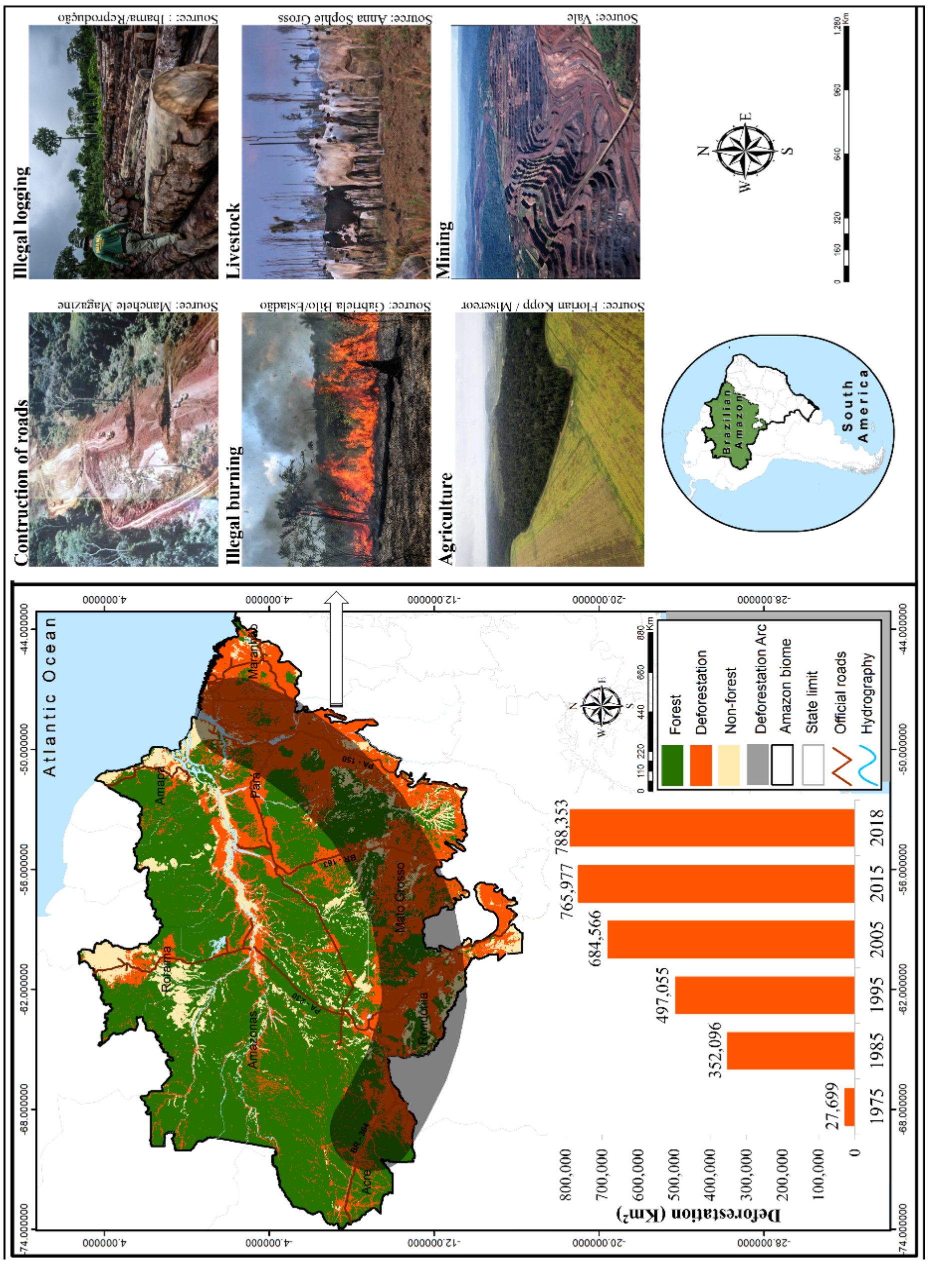

Figure 3. Deforestation in the Brazilian Amazon for the 1975-2018 period and illustration of major causes of it. The data for deforestation figures were extracted from INPE - National Institute for Space Research (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes) and CNIG (http://centrodedescargas.cnig.es/CentroDescargas/catalogo.do?Serie=CAANE).

Deforestation and forest degradation have major consequences for humankind, such as greenhouse gas emissions (Van der Werf et al., 2009, Katila et al., 2010). The estimated annual quantity of carbon emitted in the region is between 150 and 250 million tons, which represents around 10 to 15 % of the total global emissions (Houghton et al., 2000 and 2005; Dias-Filho et al., 2011). Over the years, the damage caused to the environment has decreased significantly thanks to national government actions and international interests (Rivero, 2009; Mello & Artaxo, 2017; Rodrigues, 2018; Simonet, 2019). The government has implemented several legal mechanisms against forest loss in the region; the PPCDAm - Action Plan for Deforestation Prevention and Control of the Legal Amazon, created in 2004, is among such measures (Soares-Filho et al., 2010). However, the goal of reducing illegal deforestation comes against the attitudes of Brazil's new president Jair Bolsonaro, who is not interested in protecting forests. The reflection of his comments and his development policy has resulted in high rates of forest loss and degradation since the beginning of his term (Escobar, 2019a; Artaxo, 219). Further, deforestation of the Amazon has soared under cover of the coronavirus-19 crisis (Butler, 2020; Diele-Viegas & Pereira, 2020; Barton et al., 2020; INPE, 2020).

This forest loss and degradation increase in Brazil has occurred mainly in the Amazon region, which accounted for 1,320 km^2 of deforested areas from January to August 2019, with an increase of 75% as compared to the same period in 2018 (755 km^2). August 2019 was the month with the largest degraded areas, exactly when the countless fires occurred in the Amazon. In that month alone, almost 40 thousand seats of fires were recorded in the region, an increase of 161% as compared to the same period in 2018 (15 thousand seats) (INPE, 2019; Escobar, 2019a; **Figure 4**). Despite the president's claims that Non-Governmental Organizations (NGOs) are involved with the fires in the Amazon, to "draw attention" against the government, there is evidence that fires were due to weak laws, poor supervision and incentives for the country's economic development (Pereira, 2019; Vazquez & Dey 2019; Escobar, 2019b; Artaxo, 2019). A note released by the Climate Observatory, a group that gathers approximately 50 NGOs, points out that the fires occurring in the region reflects the President's own irresponsibility towards the biome, the health of Brazilians and the climate in the world (OC, 2019).

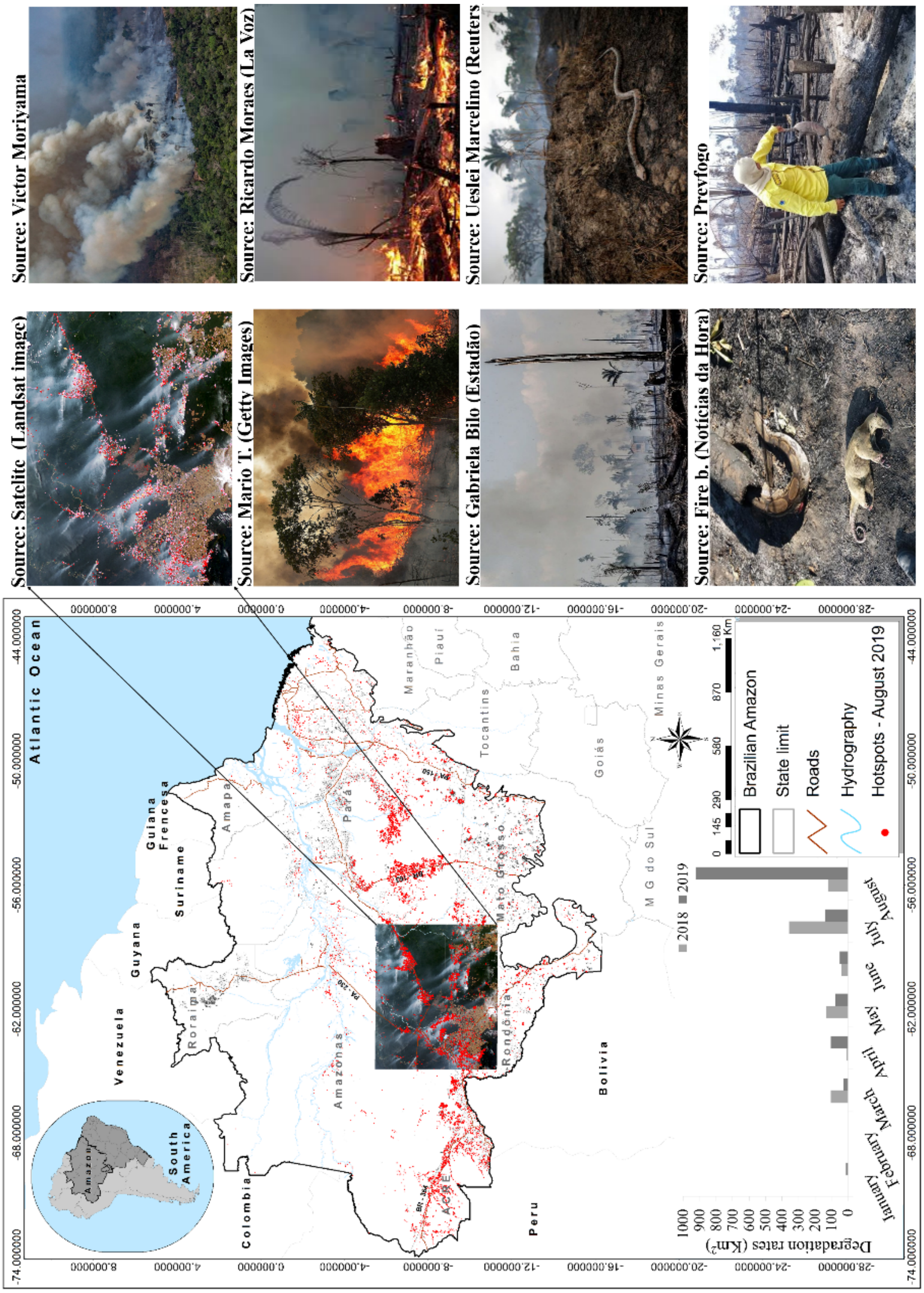

Figure 4. Map of the Brazilian Amazon with data on fire seats for the month of August 2019 by INPE, available from http://queimadas.dgi.inpe.br/queimadas/bdqueimadas/. The graph that shows forest loss increase from January to August 2018 and 2019 is based on reports by the Deforestation Alert System - SAD of the Institute of People and the Environment of the Amazon - IMAZON (https://imazon.org.br/). Next to the map is an image from NASA (Landsat/MODIS sensor) illustrating the intensity of the fires captured by satellite images and photos of the results of the fires in the region.

Biodiversity loss in Brazilian Amazon

Biodiversity reduction directly affects the provision of goods and services to humans (Balvanera et al., 2006; Cardinale, 2012; Hoeinghaus et al., 2016; Vieilledent et al., 2018; Díaz et al., 2019a). Forests are normally resilient to natural disturbances and can recover after major changes (Gunderson, 2000, Folke et al., 2004, Walker et al., 2004); however, excessive species loss reduces their resilience (Díaz et al., 2005; Pardini et al., 2010).

We are experiencing a crisis of unprecedented biodiversity loss across the planet, at a much accelerated rate, which has been induced mainly by human action (Ferreira, 2014; Richards, 2014; Díaz et al., 2019b). The magnitude of such loss is so great and so strongly linked to ecosystem processes (Thompson et al., 2013) and to the use of natural resources by society that it is currently considered of global interest (Thom & Seidl, 2016; Betts et al., 2017; Curtis et al., 2018). The Amazon, in addition to portraying some of the greatest biodiversity on the planet (Miranda et al., 2012; Barbosa et al., 2016; Tedesco et al., 2017; Barlow et al., 2018; The World Bank, 2019), is one of the biomes that has the most vulnerable characteristics to environmental variation (Seddon et al., 2016).

Biodiversity loss in the Brazilian Amazon is mainly due to deforestation of large areas for agricultural and livestock activities (Barlow et al., 2016; Hoeinghaus et al., 2016) and the introduction of exotic species (Simberloff et al., 2002, Strayer et al., 2006, Pejchar & Mooney, 2009). Forest loss generates a significant decline in goods and services (Hoeinghaus et al., 2016; Vieilledent et al., 2018). Depending on the degradation level of a given area, the financial resources used, and the recovery actions adopted, good levels of biodiversity and ecosystem services can be recovered in a relatively short period of time (Chazdon, 2008; Thompson et al., 2013; **Figure 5**).

Biodiversity loss occurs both immediately (Gibson et al., 2011; Pereira et al., 2012; He & Hubbell, 2011 and 2013; Hanski et al., 2013; Keil et al., 2015) and at long-term scales, including the extinction debt and those species committed to extinction (Shandra et al., 2010; Jackson & Sax, 2010; He & Hubbell, 2011; Wearn et al., 2012; Doherty et al., 2016; Hidasi-Neto et al., 2019). The number of living organisms lost per km^2 of forest loss is not yet known. Some authors estimate that 45 thousand to 55 thousand trees (Ter Steege et al., 2003), approximately 1,910 birds (Terborgh et al., 1990), and 35 to 81 primates (Peres & Dolman, 2000) may exist in one km^2 of the Amazon forest. When multiplying these figures by what had already been deforested by 2018 (788,535 km^2, da Cruz et al., 2020a), it is estimated that approximately 35,484,075,000 to 43,369,425,000 trees have been cut. Similarly, 1,506,101,850 birds and 27,598,725 to 63,871,335 primates may have been affected by deforestation.

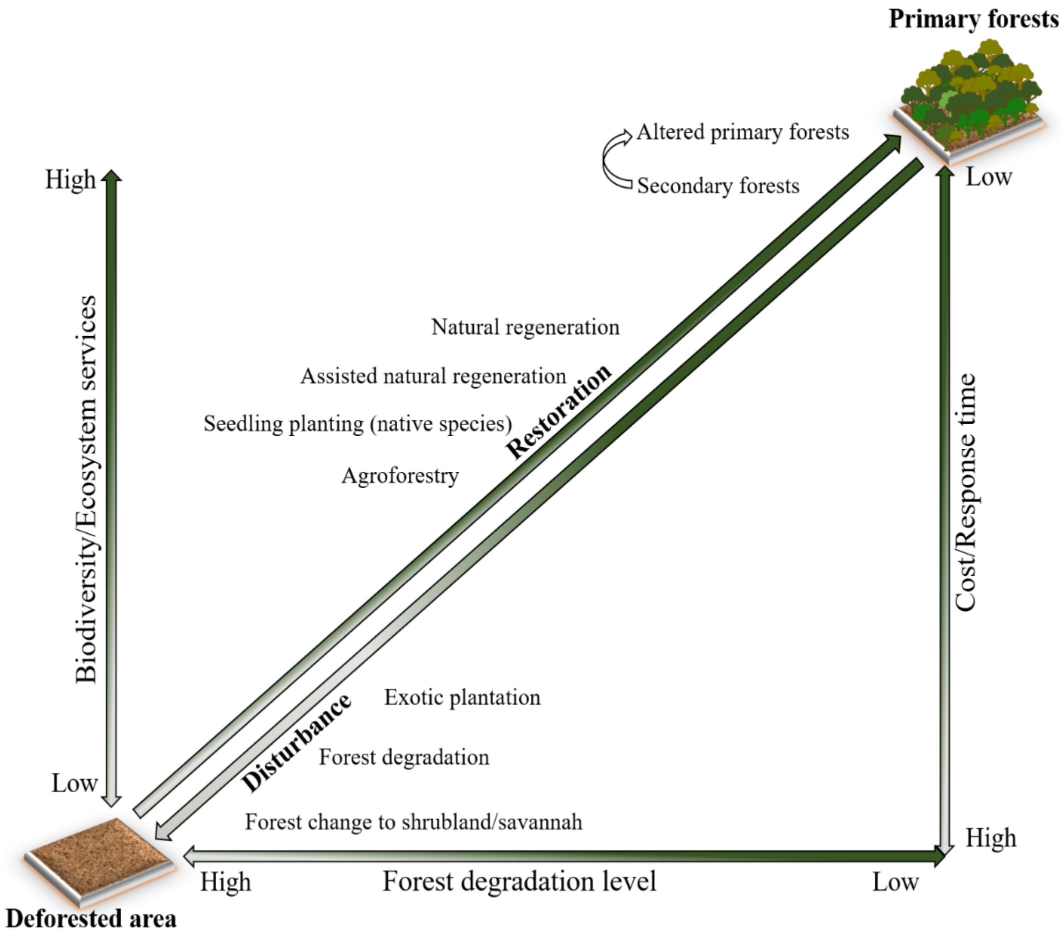

Figure 5. Co-variation of biodiversity and ecosystem services provided by forests according to a gradient of forest loss and degradation. Adapted from Chazdon, 2008 and Thompson et al., 2013. Biodiversity and ecosystem service decrease considerably with increasing levels of degradation and, conversely, they can increase with forest restoration.

There is multiple evidence that forest restoration is capable of recovering substantial levels of biodiversity and ecosystems services (Benayas et al., 2009; Stanturf, 2014; Spake et al. 2015; Crouzeilles et al. 2016; Moreno-Mateos et al., 2017; Meli et al. 2017; Jones et al., 2018; Reid et al. 2018; and Chazdon et al., 2020). However, species de-extinction it is very difficult if not impossible and extraordinarily expensive anyway (Sherkow & Greely, 2013). Thomas et al., (2004) evaluated the risk for species extinction on approximately 20% of the Earth's surface and concluded that from 15% to 37% of species would be at risk of extinction by the year 2050. For the Amazon rainforest, Feeley et al., (2009) estimated that from 5 to 9% of all species in the region are also threatened with extinction by 2050. The results reported by Miles et al., (2004) showed that persistence of 43% of the tree species analyzed in the Amazon would be compromised by the year 2095. The loss of some species significantly impairs some ecosystem services (Díaz & Cabido, 2001; Ellison et al., 2005;

He & Hubbell, 2011), and many species are rare, with small populations and, therefore, highly sensitive to any environmental changes (Terborgh et al., 2008 and 2013). For these reasons, it is thought that countless animal and plant species have gone extinct in the Amazon to date.

Approximately one million species are threatened with extinction in the world (IPBES, 2019). According to official data from the Red List by the International Union for Conservation of Nature (IUCN), approximately 27% (31 thousand species) of the more than 116 thousand different species of animals and plants are threatened with extinction in the world (IUCN, 2020). In Brazil, ICMBio (Chico Mendes Institute for Biodiversity Conservation), MMA (Ministry of the Environment) and CNCFlora/JBRJ (National Center for Plant Conservation of the Botanical Gardens of Rio de Janeiro) have updated the list of species endangered with extinction and identified 1,173 animal and 2,107 plant species (MMA, 2019). Of this total, 180 of animal species and 85 of plant species are in the Amazon region (ICMBio, 2018; **Figure 6**).

1.2. HOW TO RECOVER THE AMAZONIAN BIODIVERSITY?

We face, on one hand, the significant loss of forest biodiversity (Gibson et al., 2011; Hoeinghaus et al., 2016; Vieilledent et al., 2018) and, on the other, the need to recover millions of hectares of extirpated and degraded forest area (Menz et al., 2013; Crouzeilles et al., 2016; Lindenmayer, 2019). To address these challenges, there are some general principles that can help guide the conservation of forest biodiversity and the recovery of forest ecosystems (Lindenmayer & Franklin, 2002; Lamb, 2010). Among these principles is the need to conserve the attributes and characteristics of native ecosystems, to protect and recover populations of key species and their habitats and to maintain the main ecological processes that influence forest succession, which includes, for example, pollination and seed dispersal (Lindenmayer & Franklin, 2002).

The relationship between biodiversity, ecosystem services and landscape change has been gaining momentum in scientific studies in recent years (Tscharntke et al., 2005; Pauchard et al., 2006; Nelson et al., 2009; Haines-Young & Potschin, 2010; Bürgi et al., 2015; Brockerhoff et al., 2017; Quijas et al., 2019; Williams et al., 2020). Some studies report that numerous forest species are sensitive to forest degradation (Lindenmayer et al. 2002, Colles et al., 2009; Vranckx et al., 2012). For this reason, plant species must be carefully selected in order to achieve better results in forest restoration programs (Colles et al., 2009). Phytosociological knowledge of species groups is commonly used in

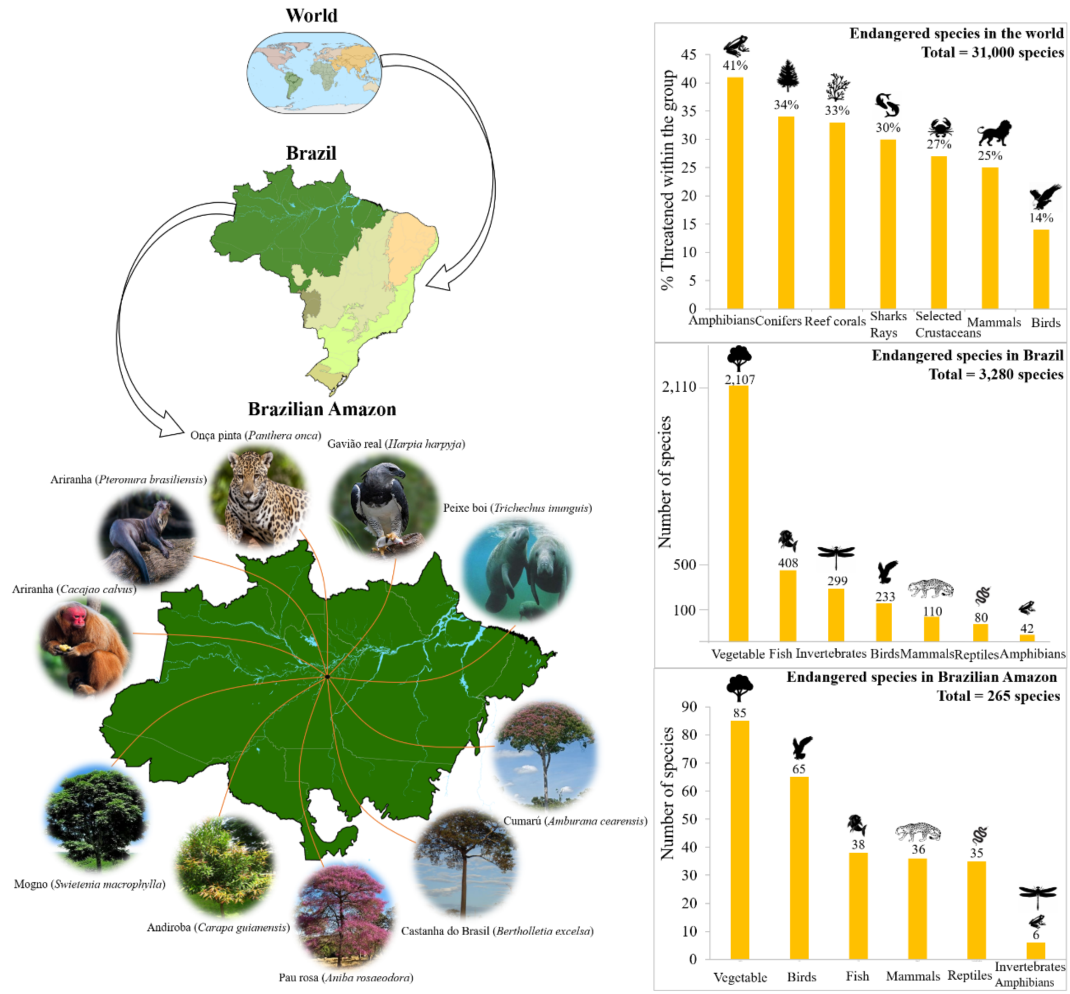

Figure 6. Species threatened with extinction in the world, in Brazil and in the Brazilian Amazon. Sources: Red List (IUCN; https://www.iucnredlist.org/) for the species threatened with extinction in the world, and ICMBio (Chico Mendes Institute for Biodiversity Conservation; https://www.icmbio.gov.br/portal/especies-ameacadas-destaque), MMA (Ministry of the Environment; https://www.mma.gov.br/biodiversidade/conservacao-de-especies/fauna-ameacada.html) and CNCFlora/JBRJ (National Center for Plant Conservation of the Botanical Gardens of Rio de Janeiro; http://www.cncflora.jbrj.gov.br/portal) for the list of species threatened in Brazil and in the Brazilian Amazon.

the Amazon as an indicator to monitor the effects of conservation and restoration actions on plant communities (Attanasio, 2008; Lewandowski et al., 2010; Neri et al., 2011; Salomão et al., 2012a; b).

The over-time evaluation of tree species composition in a forest provides information that is directly related to ecosystem change (Liebsch, 2008; Morin et al., 2018). The selected indicators are a fundamental step in the evaluation and monitoring of the recovery of degraded areas (Audino, 2014; Suganuma & Durigan, 2015; Gatica-Saavedra et al., 2017; Viani et al., 2018). Some forest species are selected in monitoring assessments because changes in population size or distribution may suggest that habitat amount or quality has changed (Kuruneri-Chitepo & Shackleton, 2011; Bjørneraas et al., 2012). Some species are more relevant than others because they have certain functions in the ecosystem (Díaz et al., 2003). The objective of forest recovery is to improve ecosystem functions without an absolute commitment to reestablishing the original plant composition (DellaSala et al., 2003; SER, 2004; Mansourian & Vallauri, 2005; Clewell & Aronson, 2007; Corbin & Holl, 2012; Stanturf, 2014; Bastin et al., 2019; Chazdon, 2019). However, it is necessary to consider the vertical structure and the main families and genera in the new restored forest (Paul & Yavitt, 2011; Salomão et al., 2012b; Hilje et al., 2015).

In addition to tree community composition, another good indicator of the forest state is the presence of certain animal groups with specific ecological functions (Díaz-García, 2017), such as pollination and seed dispersal (Wright et al., 2007; Terborgh et al., 2008). Insectivorous birds, for example, can regulate populations of herbivorous insects and act as dispersing and pollinating agents for plants (Bridgeland et al., 2010). For this reason, many insectivorous birds respond negatively to degradation in tropical forests (McCarthy, 2012; Edwards et al., 2014), and, therefore, can be used as indicators in the recovery process.

Recovery experiences have focused on species selection according to their successional stage, growth and survival (Menge & Chazdon, 2016; Boukili, 2017). It is suggested that the restorative planting should be heterogeneous by combining species from different succession stages, such as pioneers, secondary and climax (Massad et., 2011; Wang et al., 2014). These experiences have generated recovery models that have been shown to be adequate in particular areas (Meli et al., 2014; Laughlin, 2014; Lu et al., 2017). In order to define which species from a specific functional group and at what stage of the forest restoration process they will be used for restorative activities, the purpose of the work must be clearly defined (Volis, 2016; Martins, 2017; Monks et al., 2019). With good knowledge of functional groups, it is possible to propose better conservation and restoration actions for the ecosystem.

There are laws and regulations that have been created over the years and determine procedures to be adopted in forest recovery activities. Brazilian legislation, for example, requires that areas be recovered with native species to the region (Brazilian Forest Code, Law no. 12,727/2012). However, a study conducted by da Cruz et al., (2020a) identified that a large number of recovery projects used exotic species in the Brazilian Amazon. This fact can be explained by two reasons: a) a large number of commercial projects that use exotic species and b) landowners who resort to legal restrictions for the economic use of native species (Butler & Laurence, 2009).

Revegetation of a degraded area can be accomplished by a suite of different techniques with different intensity of intervention (Stanturf, 2014). Major techniques for forest restoration are a) seedling planting, b) natural regeneration, c) assisted natural regeneration by nucleation, and d) agroforestry systems (Rodrigues et al., 2015; **Figure 7**). All these restoration techniques are ultimately linked to secondary succession (Chazdon & Uriarte, 2016), i.e., they both affect and are affected by this process. Seedling planting aims to produce a forest with a starting specific composition or structure. It provides a relatively rapid tree coverage and does not depend on dispersing agents or seed sources (Stanturf, 2014; Wallertz et al., 2018). It is the most often used technique in the Brazilian Amazon (Palma & Laurance 2015; Viani et al., 2017; da Cruz et al., 2020b). Natural regeneration involves the colonization of sites by any plants and animals that may disperse from the surrounding habitats and subsequently establish themselves (Shiferaw, 2018); it therefore has a highly stochastic outcome. Assisted natural regeneration represents an intermediate technique that involves acting in focal areas for facilitating vegetation recovery (Benayas, 2008; Corbin & Holl, 2012). Nucleation, a type of assisted natural regeneration, pursues the establishment of woody recruits in these focal areas or nuclei to

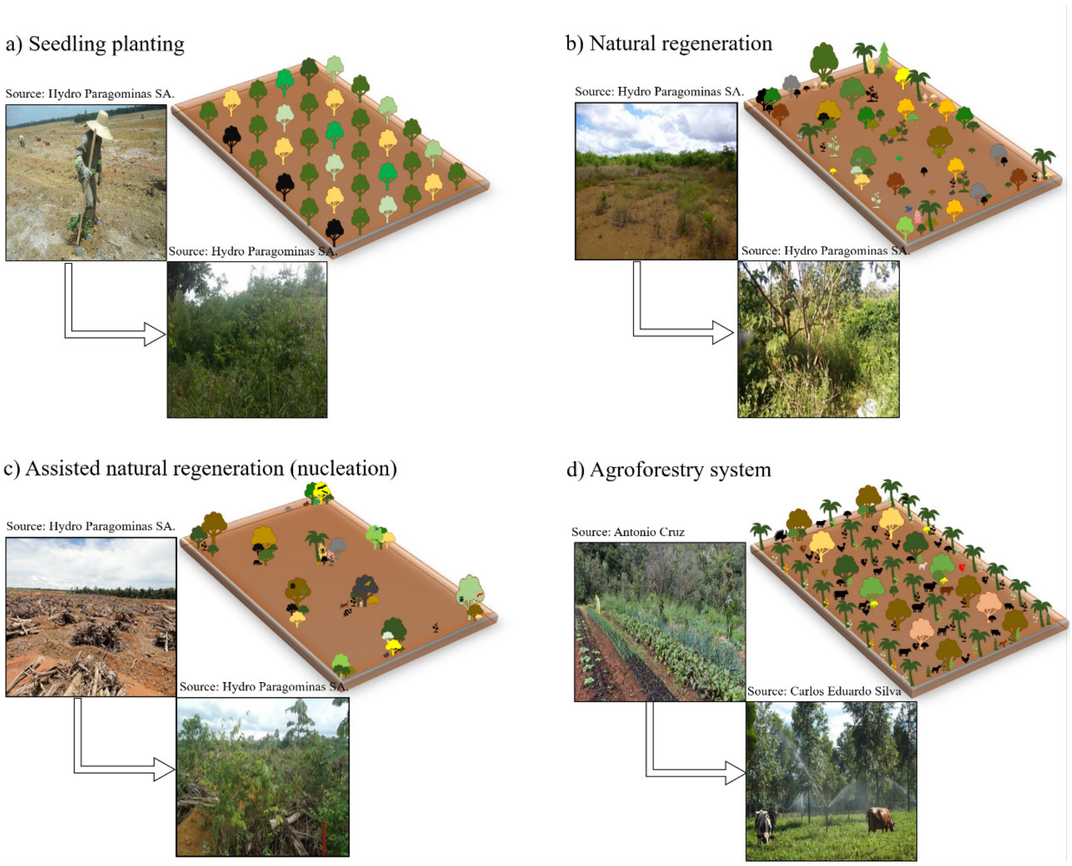

Figure 7. Some forest restoration techniques used in the Brazilian Amazon.

trigger forest expansion in larger areas over time through natural regeneration as the established nuclei attract animals that participate in seed dispersal (Benayas, 2008; Corbin & Holl, 2012). Assisted natural regeneration, which is widely used in post-mining recovery (Tomazi et al., 2010; Reis et al., 2014), seeks to facilitate natural regeneration through the cyclical relationship of producers, consumers and decomposers (Zahawi et al., 2013; Bechara et al., 2016). Finally, agroforestry systems are intercropped cultivars of tree species with agricultural crops and/or domestic animals (Martins, 2013). They enhance the structure and increase of soil nutrient levels by means of nutrient cycling promoted by roots and leaf litter accumulation (Vaz, 2000).

Choosing the best practice to recover a degraded area is still a challenge with regard to ecological restoration, as it depends on numerous factors (Nepstad, 1991; Callicott, 2002; Holl & Aide, 2011; Rodrigues et al., 2011; Similä & Junninen, 2012; Thomas et al., 2014; Chazdon & Uriarte, 2016; Burger & Zipper, 2018). Plant identification and knowledge of functional groups and ecological interactions of pollination and seed dispersal in forest dynamics are critical to understand forest regeneration (Van Breugel et al., 2019; Rozendaal et al., 2019; Barros et al., 2020) and establish appropriate recovery techniques. Therefore, selecting which techniques are most appropriate to recover a certain deforested or degraded forest requires an assessment of the changes that occur at the site, as well as an analysis of the factors that have led to such changes (Crouzeilles et al., 2016).

1.3. THE STUDY AREA

The Brazilian Amazon is a 4,196,943-km^2 territory. For this reason, only Objective 1, which is based upon satellite imagery analysis, an ad-hoc survey and a systematic literature review, is addressed in the entire region and at a long temporal scale. The three other objectives are addressed at a local scale, in the municipality of Paragominas (**Figure 8**), in the context of the Degraded Area Recovery Program in the Hydro area of the Paragominas Mining Company S.A., scoped by the Brazil-Norway Biodiversity Research Consortium (BRC). Objective 2 is addressed in the entire municipality, whereas objectives 3 and 4 are addressed in the mentioned Hydro area.

The choice of Paragominas for this Thesis also considered the fact that it was one of the Amazonian municipalities that arose during the so called period of “economic development” in Brazil, encouraged by policies established by the Brazilian government in the 1970s. Founded in 1965, it was one of the largest

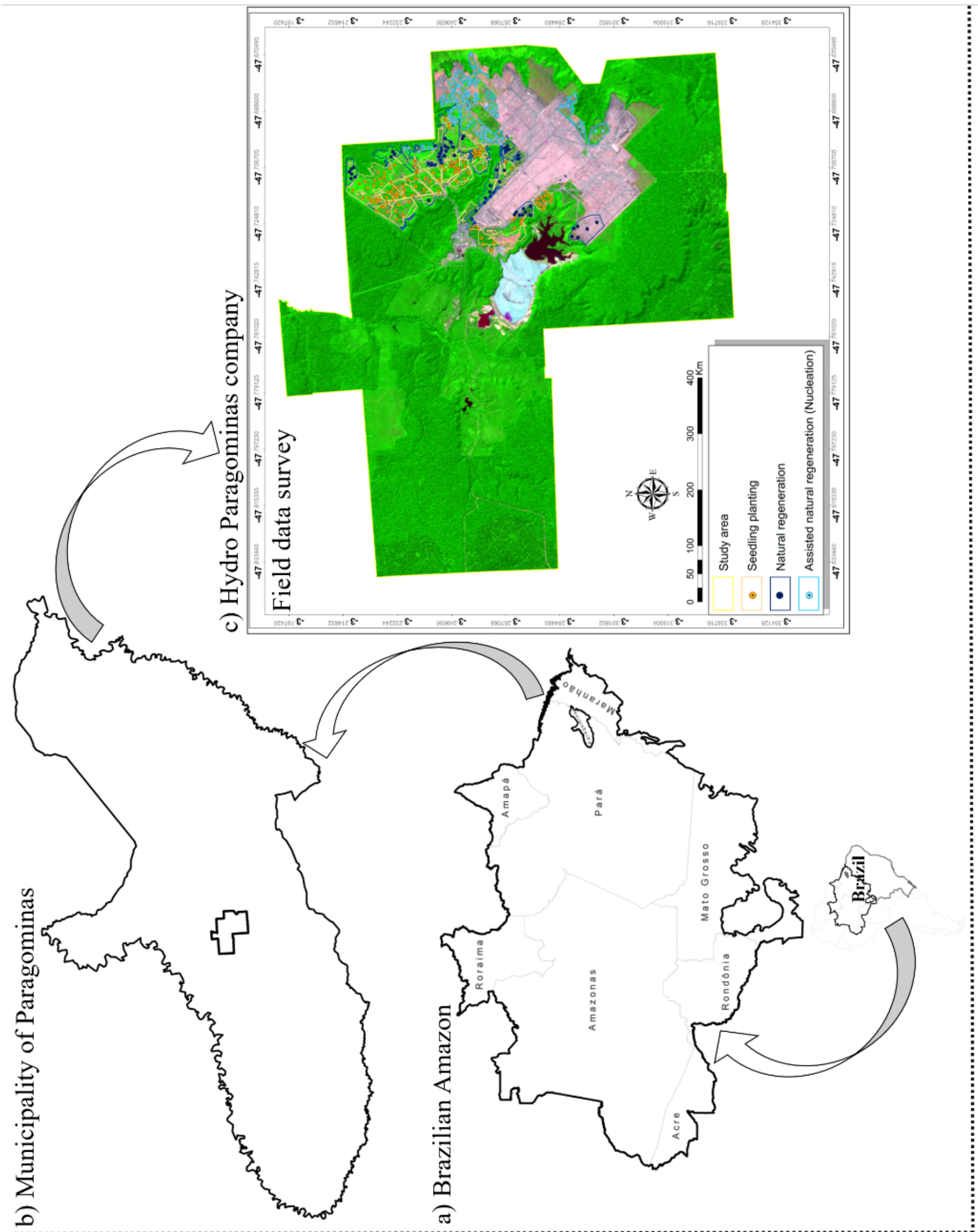

Figure 8. Map of the Thesis study area. The figure represents a) the Brazilian Amazon; b) the municipality of Paragominas; and c) the area owned by the HYDRO company.

cattle and timber producers in the country (Veríssimo et al., 1992), which resulted in high deforestation rates soon after its foundation. Located near the Belém-Brasília Highway (BR - 010), the municipality has a territorial extension of 19,342 km² and an estimated population of 113,145 inhabitants in 2019 (IBGE, 2019). The climate is hot and humid, with an average annual temperature of 26 ºC, relative humidity of approximately 80%, and an annual rainfall of 1,800 mm (Alves, 2014).

1.4. THESIS AIMS, HYPOTHESES AND QUESTIONS

The **main goal** of this Thesis, which is linked to the goal of the project that supported it (see at the start of this General Introduction), is to evaluate the forest restoration potential to enhance the provision of biodiversity and ecosystem services in the Brazilian Amazon. The **starting hypothesis** is that the Brazilian Amazon, regarded as the largest tropical forest and tree reserve in the world, one of the most biodiverse regions on the planet, and of critical importance in the light of climate change, has undergone severe deforestation and, concomitantly, offers outstanding opportunities for forest restoration that will enhance biodiversity and provide benefits to humans. The thesis has four **specific objectives**:

1. To provide an overview of forest loss, on one side, and projects, techniques, and publications on the recovery of forest degraded areas carried out in the Brazilian Amazon, on the other side. To achieve this goal, we analyzed: (1) deforestation rates in the period 1975–2018, which will be discussed within the historical, political and socioeconomic context of the region; (2) the major projects used to restore forests, on the basis of a survey conducted in environmental agencies and universities that comprised the 1950–2017 period; and (3) the results of a systematic search in Web of Science related to forest restoration between the years 1910-2018.

2. To estimate and map the vulnerability to soil erosion through geospatial analysis, by using (1) the Revised Soil Loss Universal Equation model (RUSLE) and (2) the ecodynamic concept of analysis of the physical and biotic environment. For these analyses, the following land attributes were used: (a) geology; (b) geomorphology; (c) vegetation and class use; (d) soil; and (e) climate. A complementary objective was to evaluate conservation and management practices in the Paragominas municipality by means of (a) mapping land use and land cover and assessing (b) economic historical series and (c) mining activity.

3. To evaluate the outcomes of seedling planting and natural regeneration in post-mining areas in Paragominas by means of the following selected restoration indicators: (1) degree of tree cover/shading; (2) presence of natural regeneration; (3) evidence of soil erosion; (4) forest leaf litter; (5) density; (6) diversity; (7) average height; (8) basal area; (9) mortality; (10) increase in diameter; and presence of (11) non-invasive alien species; (12) endangered species; and (13) traces of fauna return [(5) to (12) for tree species only].

4. To analyze the tree composition, the functional types, the effect of distance between the restored sites and seed sources, and the conservation status of established tree species under different forest restoration techniques (namely seedling planting, natural regeneration, and nucleation) implemented in bauxite post-mining sites. The starting hypothesis is that there are differences in tree composition and functional groups among the three forest recovery techniques (H1). It is also hypothesized that the distance from seed sources and vegetation recovery at the restored sites are negatively correlated (H2). The assessment of the formulated hypotheses will improve the forest restoration of post-mining sites in the Brazilian Amazon and other tropical areas of the world (da Cruz et al., 2020b).

1.5. THESIS STRUCTURE (CHAPTERS AND ASSOCIATED PUBLICATIONS)

This Thesis was structured in the following six chapters. **Chapter 1** provides a general introduction. **Chapters 2, 3, 4** and **5** address the actual research conducted in the Thesis, which is linked to objectives 1 to 4, respectively. They are presented as the original publications that stem from the Thesis. The summarized information of such chapters and where they were published are available in **Table 1**. **Chapter 6** reports the main conclusions of the Thesis. The “results” chapters are the following:

Chapter 2. da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C. et al. (2020). An overview of forest loss and restoration in the Brazilian Amazon. *New Forests* 51(2), 1-16. https://doi.org/10.1007/s11056-020-09777-3.

Chapter 3. da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Monteiro, A. L., & Schwartz, G. (2019). Evaluation of soil erosion process and conservation practices in the Paragominas-Pa municipality (Brazil). *Geographia Technica*, 14(1), 14-35. https://doi.org/10.21163/GT_2019.141.02.

Chapter 4. Ribeiro, S. S., da Cruz, D. C., Oliveira, F. D. A., Ferreira, G. C., Santos, D. E. (2019). Forest Restoration Evaluation Through Indicators in Areas of Bauxite Mining. *Floresta e Ambiente,* 26(3). https://doi.org/10.1590/2179-8087.081217.

Chapter 5. da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., & Ribeiro, S. S. (2020). Tree Communities in Three-Year-Old Post-Mining Sites Under Different Forest Restoration Techniques in the Brazilian Amazon. *Forests,* 11(5), 527. https://doi.org/10.3390/f11050527.

Table 1. Sequence of chapters and publications resulting from this Thesis.

	Title	Keywords	Main goal	Study area	Analysis (Data source)	Publication
1º Paper (2º Thesis chapter)	An overview of forest loss and restoration in the Brazilian Amazon	Bibliographic survey; Deforestation; Silviculture; Socioeconomic context; Succession; Tree plantation.	Overview of forest loss and restoration	Brazilian Amazon	Systematic review (PRODES data source, 12 universities, 5 major environmental agencies, Ad-hoc bibliographic).	da Cruz et al., (2020) *New Forests* (https://link.springer.com/article/10.1007/s11056-020-09777-3)
2º Paper (3º Thesis chapter)	Evaluation of soil erosion process and conservation practices in the Paragominas-Pa municipality (Brazil)	Agriculture; Environmental variables; Potential for soil loss; Amazon.	Estimate and map vulnerability to soil erosion and evaluate management and conservation practices	Paragominas municipality (Brazilian Amazon)	GIS analysis Multi-criteria analyses (CPRM, SRTM, IBGE, Satellite imagery from Landsat 8 TM, INMET).	da Cruz et al., (2019) *Geographia Technica* (http://technicalgeography.org/index.php/journal-archive/32-latest-issue-1-2019)
3º Paper (4º Thesis chapter)	Forest restoration evaluation through indicators in areas of bauxite mining	Mining; Forest succession; Topsoil.	Evaluate the outcomes of seedling planting and natural regeneration techniques	Paragominas municipality (Brazilian Amazon)	Analysis of 13 restoration indicators by Salomão et al., (2002); Rodrigues et al., (2009) and Brancalion et al., (2012) methodology, adapted for the Brazilian Amazon (PRAD data, Hydro biodiversity project).	Ribeiro, S. S. da Cruz et al., (2019) *Floram* (https://www.floram.org/journal/floram/article/doi/10.1590/2179-8087.081217)
4º Paper (5º Thesis Chapter)	Tree communities in 3-yr-old post-mining sites under different forest restoration techniques in the Brazilian Amazon	Dispersion; Importance Value Index; Pollination; Seed sources.	Analyze species composition, functional groups, effect of distance between restored sites and seed sources, and conservation status of tree species under different forest restoration techniques.	Paragominas municipality (Brazilian Amazon)	Field data; resampling technique, Linear models, Floristic analyses (PRAD data, Hydro biodiversity project).	da Cruz et al., (2020) *Forests* (https://www.mdpi.com/1999-4907/11/5/527)

Satellite Monitoring System of the Brazilian Amazon Forest (PRODES)/ Brazilian Geological Service (CPRM)/ Shuttle Radar Topography Mission – (SRTM)/ Brazilian Institute of Geography and Statistics (IBGE)/ National meteorological institute (INMET)/ Degraded Area Recovery Program (PRAD).

1.6. REFERENCES

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2. AN OVERVIEW OF FOREST LOSS AND RESTORATION IN THE BRAZILIAN AMAZON

CHAPTER II

An overview of forest loss and restoration in the Brazilian Amazon*

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ABSTRACT

Forest restoration is a strategy to reverse forest loss and degradation. We overviewed deforestation in the period 1975-2018 in the Brazilian Amazon and the projects, techniques, and scientific publications conducted to recover forest in the area by 2019. We used GIS to assess forest loss and a systematic data collection gathered from 12 universities, five major environmental agencies, and an ad-hoc bibliographic survey that rendered information from 405 restoration projects and 152 published studies. The Brazilian Amazon has undergone an accelerated deforestation in the last 43 years, resulting in 20% (788,353 km²) of its territory deforested by 2018. Deforestation rate was 27,033 km² yr-1 between 1975 and 1987 and 14,542 km² yr-1 between 1988 and 2018 (1.97% yr-1 of forest loss between 1975 and 2018). In 2018, 41 Amazonian municipalities were classified as priority areas for monitoring and control deforestation and 21 additional municipalities were deemed as areas with controlled deforestation. Our survey identified 405 projects of forest restoration in 191 municipalities between 1950 and 2017. The majority (229) of these projects used seedling planting as the main forest restoration technique. Forest restoration projects based upon agroforestry systems (144), assisted natural regeneration (27), and natural regeneration (5) were also identified. Despite a considerable number of projects and publications, the region still lacks scientific studies that reinforce the choice of best practices for forest restoration, and the information currently available is not enough to quantify what has already been recovered or the potential area to be restored.

Keywords: Bibliographic survey, deforestation, silviculture, socioeconomic context, succession, tree plantation.

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2.1. INTRODUCTION

Human activities have resulted in large worldwide extents of forest loss and degradation (Kindermann et al. 2008; Hansen et al. 2013) and the associated loss of biodiversity, functions and ecosystem services such as water provision, nutrient cycling and climate regulation (Thompson et al. 2013). Forest loss and degradation greatly affect human well-being, including economy and health (Newman et al. 2014; Liu et al. 2016).

The ability of forests to withstand disturbance and to recover is variable (Fahey et al. 2016; O'Connor et al. 2017), and some studies point to secondary forests as highly valuable for biodiversity conservation (Crouzeilles et al. 2016; Lindenmayer 2019). A number of forest restoration techniques and methods have stemmed from different professional guilds including silviculturists, agroforesters and ecologists (Sarr and Puettmann 2008; Stanturf et al. 2014a). However, traditionally, forest restoration aimed at recovering the same or very close conditions of the original forest (Stanturf et al. 2014b). Landscape forest restoration is mostly based upon active revegetation (Ciccarese 2012; Gilman 2016), natural regeneration or mixed approaches, which can be accomplished by planting seedlings of native and/or exotic species, natural regeneration, assisted natural regeneration, or establishing agroforestry systems (Stanturf 2014a; Macdonald 2015; Viani et al. 2017). The most currently used technique beyond natural regeneration to restore deforested areas is seedling planting (Palma and Laurance 2015; Grossnickle 2017; Freitas et al. 2019).

In the Brazilian Amazon, the conversion to pastureland and cropland, road opening, fires, and wood and ore extraction have historically been the main causes of forest loss and degradation (Solar et al. 2016). As a result, numerous environmental and social problems have been documented in the region, including biodiversity loss (Barlow et al. 2016; Winemiller et al. 2016), greenhouse gas emissions (Sarmiento et al. 2010; Pearson et al. 2017; Song et al. 2018), and the decline of traditional cultures (Fearnside 2002), which generate concern and awareness regarding the need of natural resource conservation (Malhi et al. 2014). Forest loss and degradation in the Brazilian Amazon has gained strong momentum under the current President Bolsonaro's government, which is leading the country to "its worst recession and political divisions in a generation—a daunting time to take up the reins. Unfortunately, his immediate solutions are a threat to the Amazon forest—a resource that most Brazilians want to protect" (Artaxo 2019). Bolsonaro claims that the recent Amazon burnings are the result of climate change; however, scientists have dismissed this statement and reinforce the idea that the numerous fires in the region and, consequently, forest loss and degradation are motivated by a weaker environmental law and encouraged development (Escobar 2019a). Deforestation in the region has been on the rise since the beginning of Bolsonaro´s mandate (Escobar 2019b).

According to the DEGRAD/INPE (Brazilian National Institute for Space Research) system, which monitors forest loss and degradation in the Brazilian Amazon, approximately 138,516 km² of degraded areas were mapped in the region from 2007 to 2019. There have been records of restoration projects in degraded areas in Brazil since 1862, when the current Tijuca Forest located at Rio de Janeiro state was reforested. However, the first steps towards forest restoration based on scientific research in the Amazon began in the 1970s through reclamation programs in Rio do Norte Mining areas depleted by bauxite exploitation, with some experiments carried out in academic environments (Brancalion 2015). The selection of the most appropriate technique(s) to restore a given lost or degraded forest requires to evaluate changes occurring in the site as well as an analysis of factors that led to loss or degradation (Hutto 2014; Crouzeilles et al. 2016).

The aim of this study is to provide an overview of forest loss, on one side, and projects, techniques, and publications on the recovery of degraded areas carried out in the Brazilian Amazon, on the other side. To achieve this goal, we analyzed: (1) deforestation rates in the period 1975-2018, which will be discussed within the historical, political and socioeconomic context of the region; (2) the major projects used to restore forests, on the basis of a survey conducted in environmental agencies and universities that comprised the 1950-2017 period; and (3) the results of a systematic search in Web of Science related to forest restoration between the years 1910 to 2018.

2.2. METHODS

2.2.1. Forest loss in the period 1975-2018

We analyzed deforestation rates in the Brazilian Amazon for the period 1975-2018 with data from the Amazon Deforestation Calculation Program (PRODES/INPE; http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes; Piketty et al. 2015). The PRODES method measures the extent of annual deforestation in the Brazilian Amazon through satellite image classification, from an average pixel spatial resolution of 0.36 ha. The land cover classes considered in the program classification are forest, deforestation, non-forest area, hydrology, and cloud area. The PRODES database is available every year in a vector, shapefile file format. We used ArcGis© 10.1 GIS software (Esri

2012) to map all vector files analyzed here, and mapped data were later exported to Excel© for the generation of statistics and graphs. We estimated deforestation rates for two periods, namely 1975-1987 and 1988-2018. Estimates for the period 1975-1987 were extracted from INPE´s deforestation reports, whereas estimates for the period 1988-2018 were directly obtained by the authors of this study.

We also analyzed the priority areas to combat and control deforestation in the Brazilian Amazon. The detection of high illegal deforestation rates led the federal Government to issue Decree No. 6,321/2007 that established measures to prevent, monitor, and control deforestation. A “black list” of the most deforested municipalities in the Amazon was created as a result of this decree, which became a priority for surveillance and monitoring actions through the Rural Environmental Registry (*Cadastro Ambiental Rural*). This list has been published annually by the Environment Ministry (*Ministério de Meio Ambiente*) based on the following criteria: i) total deforested area; ii) total deforested area in the last three years; and iii) an increase in deforestation rates in at least three of the last five years. Once in the black list, landowners are imposed with transport and document restrictions to sell their products (Ordinance No. 362/2017). In order to leave this black list and join the “green list” of municipalities deemed as of controlled deforestation, the municipality must maintain deforestation under 40 km² in the last four years and 80% of its territory.

2.2.2. Survey of forest restoration projects

We systematically surveyed forest restoration projects in the Brazilian Amazon between 1950 and 2017 in the repositories of 12 universities and five major environmental agencies (**Table S1**). For each assessed project, we looked at (1) the used restoration technique (i.e. seedling planting, agroforestry, assisted natural regeneration, and natural regeneration); (2) the financing support; and (3) the species type used for restoration (native and/or exotic).

2.2.3. Survey of the scientific literature

We carried out a systematic search in Web of Science to assess forest restoration in the Brazilian Amazon. The search pursued all publications between 1910 and 2018 with selected keywords in the title. The Boolean operator used was OR between the following terms: “area* reclamat*”, “area* recov*”, “ecologic* restorat*”, “environmental restorat*”, “forest recove*”, “forest rehabilitat*”, “forest remediat*”, “forest restorat*”, “land reclamat*”, “recov* degrad*”, “reforest*”, “rehabilitat* forest”, “rehabilitation of degrad*”, “remediation degrad*”, remediation of degrad*”, “remediation of forest”, “restorat* of tropical”, and “revegetat*”; the operator AND linked to “Brazilian Amazon”.

In this search, only 152 studies published since 1985 were identified. We assessed (1) the number of published studies per year, (2) the institution that supported the involved research; (3) type of publication (i.e. international or national journals and other Brazilian publication types); (4) the used restoration technique (see categories in the previous section); (5) the species type (see above); and (6) the major topic of research addressed by each study.

We assessed as well the network structure of the identified published studies in terms of connectivity among studies based on the words in the title and in the abstract and on the journals where they were published. The individual studies were grouped into clusters by means of VOSviewer (Van and Waltman 2017; www.vosviewer.com), a software tool for constructing and visualizing bibliometric networks.

2.3. RESULTS

2.3.1. Forest loss in the period 1975-2018

The results of our analysis of deforestation in the Brazilian Amazon based upon the INPE reports are summarized in **Fig. 1** and **Fig. S1**. Overall, deforestation rate was 27,033 km^2 yr^{-1} between 1975 and 1987 and 14,542 km^2 yr^{-1} between 1988 and 2018, resulting in 1.97% yr^{-1} of forest loss for the 1975-2018 period (**Fig. S1)**, with a net forest loss of 760,654 km^2. In 1975, when large development projects were created or started, 27,699 km^2 (0.5%) of deforested area was identified

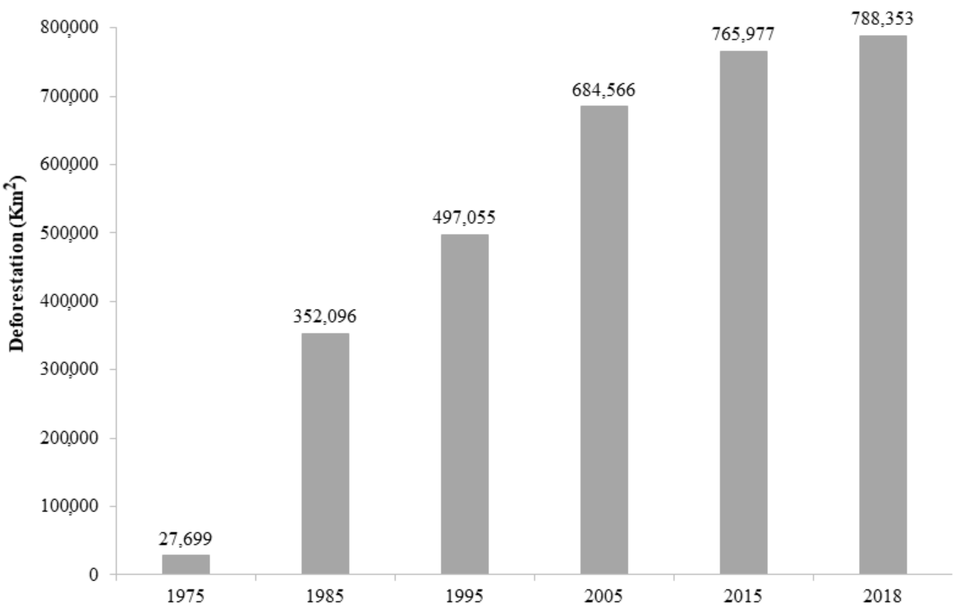

Fig. 1 Deforestation extension in the Brazilian Amazon between 1975 and 2018 based on PRODES-INPE (Satellite Monitoring Project of the Brazilian Amazon Forest – Projeto de Monitoramento da Floresta Amazônica Brasileira por Satélite).

(**Fig. 1**). Ten years later, deforestation attained 352,096 km^2 (7%), an increase of 1,171% since 1975. After 1985, deforestation continued to advance but at lower rates; thus, forest loss in 2015 and 2018 are quite similar (765,977 km^2 or 19.26% and 788,353 km^2 or 20%; **Fig. 1**). The map of **Fig. 2** shows current remaining forest, non-forest biome, and deforested land until 1987 and until 2018.

By 2007, 45% (5,175 km^2) of all deforested land in the Brazilian Amazon occurred in the 36 so far priority municipalities to combat and control deforestation. By 2018, 41 Amazonian municipalities were classified as priorities and 21 additional municipalities were deemed as of controlled deforestation. Deforestation accumulated in these 41 municipalities represented 23% (183,567 km^2) of deforested area in the region. On the other side, the 21 municipalities with controlled deforestation comprised 11% (82,058 km^2) of deforested area by 2018. Further, between 2007 and 2018, the referred 41 and 21 municipalities underwent a total deforestation amount of 4.4% and 3.9% of their land, respectively. The remaining 713 (66%, 520,313 km^2) municipalities were not in the priority list to combat and control deforestation (**Fig. 3**, **Table S2**).

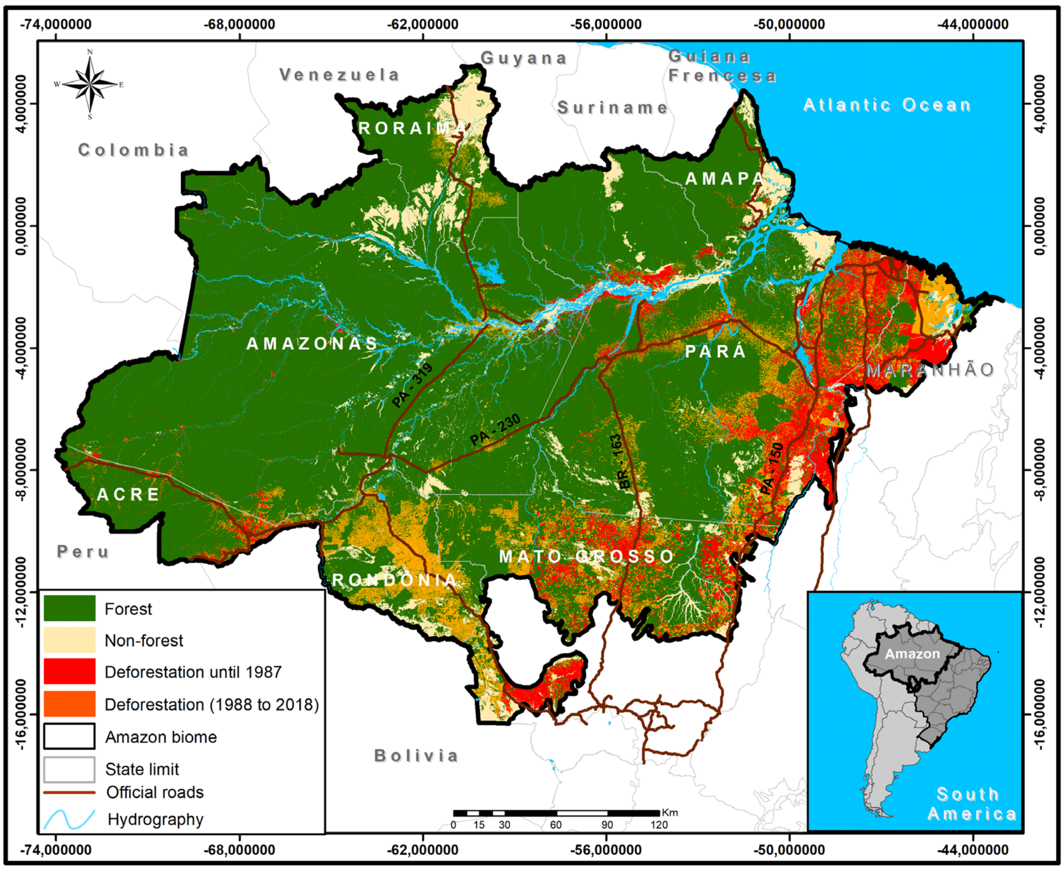

Fig. 2 Forest, non-forest, and deforested area in the Brazilian Amazon by 2018. The deforested area by 1987 is also distinguished. This map is based on data from PRODES-INPE. We used ARCGIS (Esri 2012) for mapping and area calculations

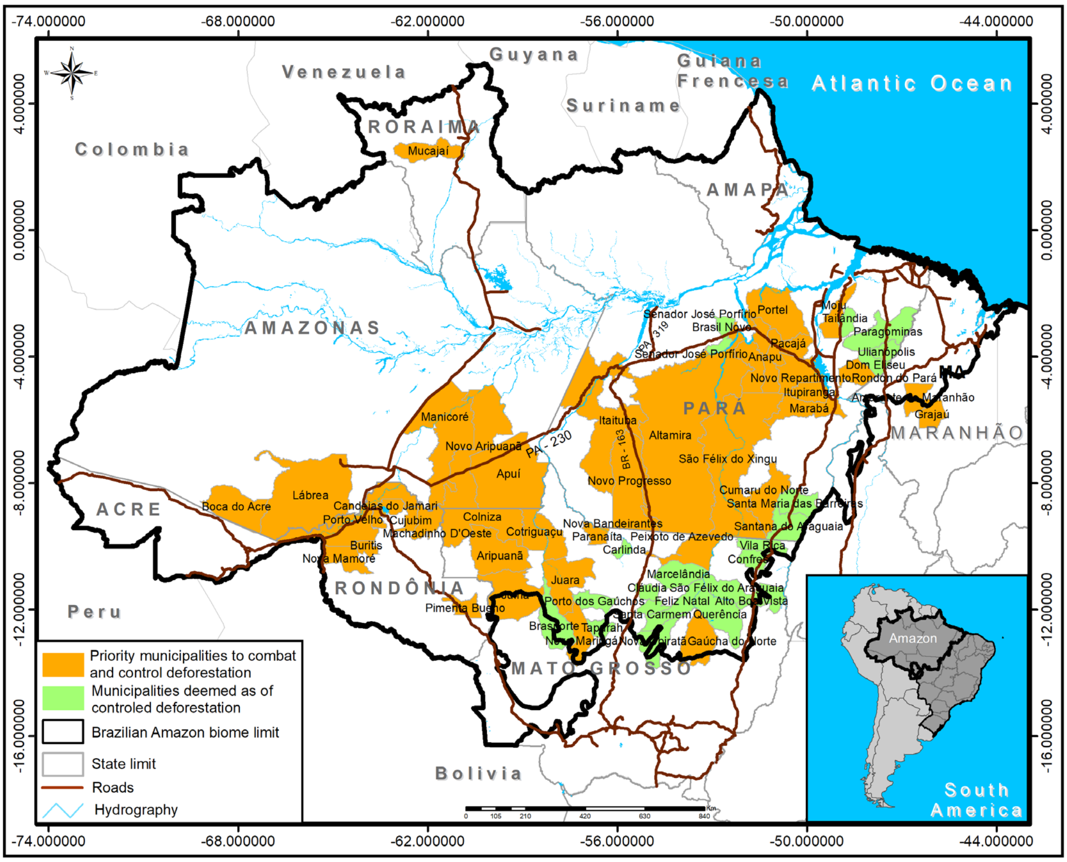

Fig. 3 Distribution of priority municipalities to combat and control deforestation and of municipalities deemed as of controlled deforestation in the Brazilian Amazon by 2017. This map based on data from MMA/geographic database of IBGE –https://ibge.gov.br/ (Ordinance No. 361, DOU of 09/13/2017 and No. 176, Section 1, p. 69).

2.3.2. Forest restoration projects and techniques to recover forest

We identified 405 projects located in 191 municipalities in the Brazilian Amazon that were run between 1950 and 2017 (**Fig. 4**). These projects were established and managed by governmental (6 projects, 1.5%) and non-governmental (2, 0.5%) organizations, forestry companies (202, 50%), and family farmers (195, 48%). The commercial tree plantations mainly used exotic tree species such as teak (*Tectona grandis*), acacia (*Acacia mangium*), and eucalyptus (*Eucalyptus* spp.), and fulfilled only part of the legal constraints in environmental licensing required to restore degraded lands in the Brazilian Amazon. The techniques used to restore forest land were seedling planting (229 projects, 57%), agroforestry (144, 36%), assisted natural regeneration (27, 7%), and natural regeneration (5, 1%; **Fig. S2a)**.

These restoration projects were financially supported by private companies (129 projects, 32%), agreements between federal and state research institute and

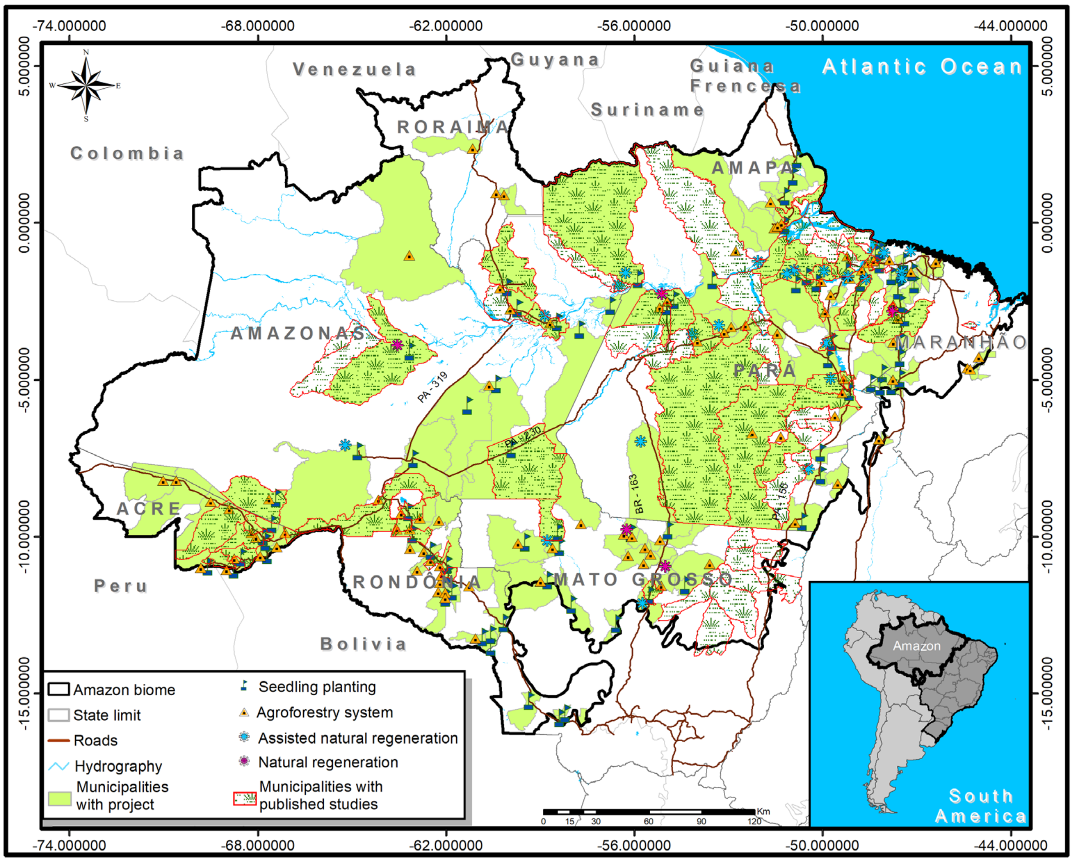

Fig. 4 Location of the 191 municipalities with forest restoration projects and published studies in the Brazilian Amazon that were run between 1950 and 2017. Projects are classified according to four major techniques used to restore forests in the region.

environmental agencies (37, 9%) and private companies (36, 9%), environmental agencies (33, 8%), the National Research Institute (19, 5%), and agreements between international research institutes and private companies (9, 2%); the support for 142 projects (35%) could not be identified in our survey (**Fig. S2b**). The restoration projects used native species (148 projects, 36%), exotic species (121, 30%) and both native and exotic species (55, 14%); 81 projects (20%) did not report any information on the type of species used (**Fig. S2c**).

2.3.3. Scientific production

The 152 studies published since 1985 that were identified in our literature survey belonged to nine areas of knowledge. They received 3,224 citations in total and the number of publications grew exponentially since 2011 (**Fig. S3a**). The leading institutions of authors were Embrapa (21 publications), the National Institute of Amazonian Research (14) and the Emilio Goeldi Museum (10).

The articles were published in 73 different (45 international and 28 national) scientific journals including *Forest Ecology and Management* (14 publications), *Acta Amazônica* (7), *Forest Science* (5), *Restoration Ecology* (5), and *Revista Árvore* (4).

The studies were carried out in 87 municipalities, of which only 35 were included in the 191 municipalities of restoration projects analyzed in the previous section (**Fig. 4**). Some 112 published studies (74%) reported the source of research support, namely research institutes (37 studies, 24%), private companies (23, 15%), federal and state governmental environmental bodies (19, 13%), and agreements among all these institutions (**Fig. S3b**). Other types of publications were also identified, such as reports by Embrapa - Brazilian Agricultural Research Corporation, congress proceedings, and Master's and PhD theses (**Fig. S3c**).

The techniques to restore forests that were identified in the published studies were natural regeneration (59 published studies, 39%), seedling planting (54, 36%), agroforestry systems (21, 14%), assisted natural regeneration (5, 3%), and more than one technique (8, 5%). Five studies were conducted on priority areas for forest restoration (**Fig. S3d**).

Most of the published studies (98, 65%) used native species to restore forests, whereas 22 (14%) used both native and exotic species, only one study (1%) used exotic species, and 31 (20%) projects did not report this information (**Fig. S3e**). The main topics addressed by these studies were: (a) vegetation structure and phytosociological characterization (67 published studies, 44%); (b) assessment of soil properties and vegetation carbon (16, 11%); (c) overviews related to forest restoration (18, 12%), and (d) restoration techniques (12, 8%) (**Fig. S3f**).

The assessment of the network structure of the identified published studies, in terms of connectivity among studies based on the words in the title and in the abstract, resulted in four clusters that are shown in **Fig 5**. The blue cluster was mostly related to floristic composition, the red cluster to forest loss and degradation, the green cluster to restoration techniques, and the yellow cluster to vegetation growth. The assessment of the network structure based on the journals where the studies were published highlighted six clusters led by the journals *Forest Ecology & Management* (red color), *Restoration Ecology* (navy blue), *J. of Range Management* (brown), *Science of the Total Environment* (green), *Forestry Chronicle* (orange), and *Agriculture Ecosystems & the Environment* (yellow, **Fig S4**).

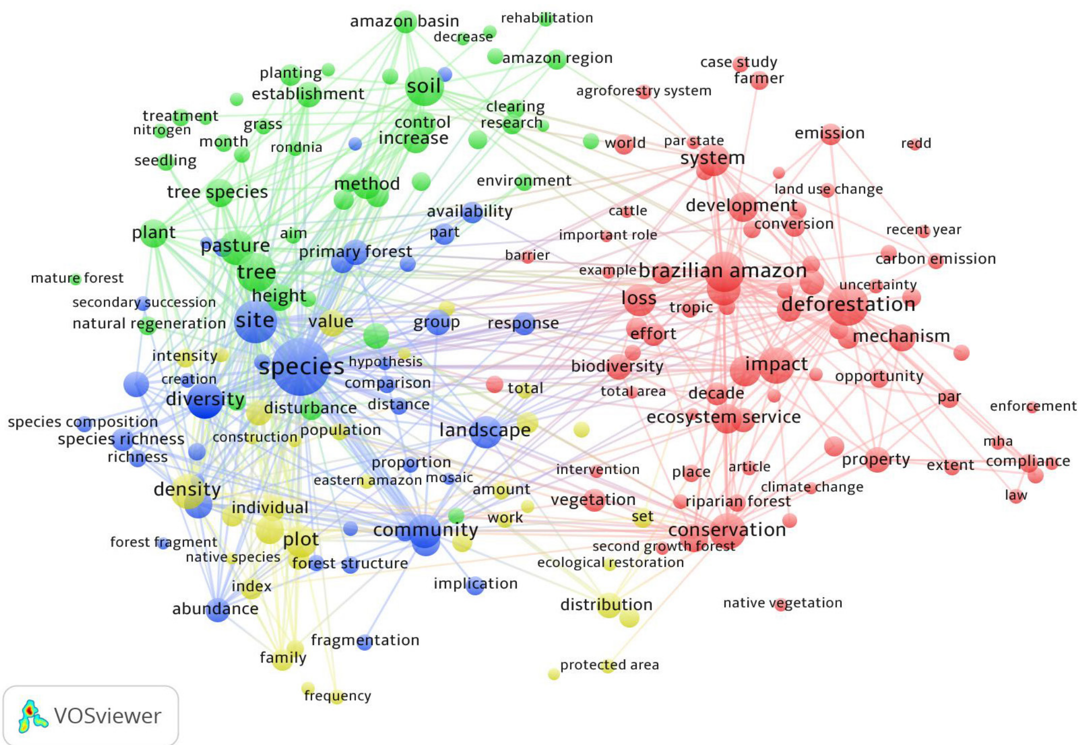

Fig. 5 Connectivity map of published forest restoration studies in the Brazilian Amazon based on the words in the titles and the abstracts. Frequency of studies is proportional to colored balls and font size.

2.4. DISCUSSION

Overall, our overview of forest loss and restoration in the Brazilian Amazon hinted enormous deforestation rates starting in the 1970s and efforts to reverse this deforestation by means of forest restoration projects that were partly triggered by scientific and technical published research. Other studies have pointed to high deforestation rates in the Amazonia (Souza Jr et al. 2013; Barber et al. 2014) and in other areas of Central and South America (Steininger et al. 2001; Echeverría et al. 2006; Armenter et al. 2006; Swenson et al. 2011).

2.4.1. Historical, political and socioeconomic context of forest loss and degradation in the Brazilian Amazon

The 17th and 18th centuries were marked by intense alteration of the Amazonian landscape, initially due to overexploitation of timber and non-timber forest products, which was followed by intense agricultural activity in the 19th and 20th centuries (Batista 2007). For example, the exploitation of rubber tree latex brought 500,000 migrants to the region between 1850 and 1945, who sought survival due to intense drought and work opportunities in the rubber tree plantations (Benchimol 1977). A second intense period of changes began in the mid-20th century due to deforestation for infrastructure, which was encouraged by the Brazilian government to colonize and develop the region. Large projects were implemented in the country by that time (Hall 1989; Mahar 1979), e.g. the construction of large highways such as the Transamazônica (Oliveira 2017). This development period was influenced by the creation of the SPVEA (Superintendence for the Amazon Economic Valuation Plan − Superintendência do Plano de Valorização Econômica da Amazônia) and the PDA (Development Plan of the Amazon − Plano de Desenvolvimento da Amazônia), which stemmed out from the 1st PND (National Development Plan − Plano Nacional de Desenvolvimento).

The exploitation of natural resources in the Amazon was intensified after 1970. In response to the first oil crisis (Nye 2002), the government of the Brazilian president Ernesto Beckmann Geisel (1974 to 1979) created the 2nd PND that promoted the expansion of the infrastructure, transportation, energy and communication sectors, as well as exports of Amazonian products (Fonseca 2008). The Polamazonia (Agricultural and Agromineral Poles of Amazon) was created in 1974 to boost and develop the economy in the Brazilian Amazon through a set of economic activities and government tax incentives to attract companies to the region (Monteiro 2005). This program fostered the largest (900,000 km^2) mineral extraction project ever implemented in tropical forests worldwide − The Great Carajas Project (Projeto Carajás Grande - PGC) (Mesquita 2015). The 3rd PND was established in 1979 with the same focus of "integration and occupation" motto coupled with expanding exports aiming at minimizing foreign debt related to the second oil crisis (Goldenberg 2003). By this time, the Polonoroeste (The Northwest Brazil Integrated Development Program − Programa de Desenvolvimento Integrado do Noroeste do Brasil) was implemented in the Amazon in 1981. Deforestation in the Amazon increased significantly with the implementation of this program, mainly due to the agricultural activity. This agricultural activity mostly benefited large (*latifundium*) landowners and, as a consequence, several agrarian conflicts raised and brought instability and violence to the region (Pereira 2016).

A milestone in the country's history was the implementation of the Real currency in 1994, which coincided with exports of soy and meat (Arima et al. 2014) and resulted in high deforestation rates in 1995. Deforestation rose again in the early 2000s, which led the Brazilian Federal Government to create the PPCDAm (Action Plan for Prevention and Control of Deforestation in the Legal Amazon) in 2004. One year after PPCDAm operation, deforestation was reduced mainly as the result of the new established and expansion of the existing protected areas (Soares-Filho 2010). Another reason for this reduction was the strong international pressure against environmental crimes in the Amazon, including the murder of US missionary Dorothy Stang in 2005 (Le Breton 2008). The current version of PPCDAm (2016-2020) aims at reducing deforestation rates in the region by 80% by 2020. This goal is quite ambitious, considering the attitudes of the current Brazilian President, who apparently is not interested in protecting and restoring forests. Current deforestation rates are greater than in the near past and are expected to rise in the near future (Escobar 2019a; Artaxo 2019).

2.4.2. Forest conservation and restoration in the Brazilian Amazon

In spite historical changes in forest extent in the Brazilian Amazon have resulted in the deforestation of large areas (Prates and Bacha 2011), the efforts to redress this trend are also noticeable. These efforts have been mostly led by the Federal Government through the implementation of legal instruments, which obligate private companies to restore the forest cover in the areas they degrade (further explanation in **Appendix S1** and **Table S3)**. The regulatory laws in the country were initiated with the creation of the IBDF - Brazilian Institute of Forest Development (Federal Decree No. 289, 1967), the SEMA - Secretariat of the Environment (Decree No. 73030, 1973), and the CONAMA - National Environment Council and the SISNAMA - National System for the Environment (Law 6.938, 1981). Nevertheless, the most outstanding initiatives led by the Federal Government started in the mid-2000s. The PPCDAm and its positive effect in forest protection was commented earlier.

The federal government has also been taking environmental planning measures at the municipality level through the establishment of priority areas to combat and control deforestation in the Brazilian Amazon (Decree No. 6,321/2007). In the light of the deforested area in the 36 priority municipalities by 2007, i.e. 45% or 5,175 km^2 of all deforested land in the 775 municipalities that comprise the Brazilian Amazon, we can conclude that the selection of such municipalities was correct. However, since the implementation of this measure, the list of priority municipalities has increased and reached 62 municipalities in 2018. Most of these municipalities are located in the Pará, Mato Grosso and Rondônia states, which are part of the “Deforestation Arc”, an area of agricultural frontier expansion, tension and conflicts (Ferreira et al. 2005; Castro 2008). Further, the 21 municipalities deemed as of controlled deforestation underwent a deforestation of just ca. 12% less than the deforestation in the 41 priority municipalities, meaning that this measure has not actually been very successful.

In the last two decades, knowledge on the outcomes of forest restoration has increased significantly (see recent meta-analyses by e.g. Spake et al. 2015; Crouzeilles et al. 2016; Meli et al. 2017; and Reid et al. 2018). These and other studies usually distinguish between passive and active forest restoration. Most restoration projects in the Brazilian Amazon use seedling planting as the main technique (Palma and Laurance 2015; Chaves et al. 2015; Viani et al. 2017), also evidenced in the survey conducted in this study. This technique provides good soil cover, greater species diversity and does not depend on dispersing agents or seed sources (Wallertz 2018). We found projects that use one or a few fast-growing species and others that use more than a hundred species (Kanowski 2010; Rodrigues et al. 2011; Newton 2015). These projects aim to shade aggressive species, attract seed dispersers from neighboring forests, and improve microclimate and soil conditions (Kanowski 2010; Shoo and Catterall 2013). Brazilian law requires that the areas be restored with native species of the region (Brazilian Forest Code, No. 12.727 / 2012); however, in this study, we identified a large number of restoration projects using exotic species. This fact can be explained by the large number of commercial projects that use exotic species and because land owners trip on legal restrictions for economic use of native species (Butler & Laurence 2009). Agroforestry systems is another frequently used technique used to link economic and conservation interests when recovering degraded areas (Dubois 1996). The use of these systems has been increased mostly in the Eastern Amazon over the last 15 years. For instance, Japanese immigrants in the municipality of Tomé-Açu (Pará) are producing large amounts of crops, tropical fruits, cocoa seeds, and timber while maintaining ecosystem services typical of forests (Yamada 2006). On the other side, assisted natural regeneration seems to be an underused restoration technique (Chazdon & Uriarte 2016).

2.4.3. Scientific production

In the last 30 years, there has been progress in the area of ecological restoration in the Brazilian Amazon, especially on studies involving forest dynamics and analyses of species of different functional groups (Rodrigues et al. 2009). However, despite the numerous (405) restoration projects identified in this study, we found few scientific publications (152). In addition, the published studies were originated at only 47 of the 191 municipalities where we identified forest restoration projects.

The first scientific study on ecological restoration in the Brazilian Amazonian took place in 1970 and was motivated by planting models developed by universities and research institutions (Brancalion 2015). National and international scientific research on forest restoration was born with the growing and urgent demand on the subject. In 1987, the International Society for Ecological Restoration was created, with the first volume (Ecological Restoration) published in 1993. During this period, the first restoration groups of degraded environments emerged in Brazil, namely: Sobre (Brazilian Society of Ecological Restoration), Rebre (Brazilian Network for Ecological Restoration) and Sobrade (Brazilian Society for the Recovery of Degraded Areas).

Bibliographic review is crucial to have a good theoretical background (Conboy 2009; Li 2016) and support research (Webster & Watson 2002). In our review and connectivity analysis, we identified a high density and strong relationship among the terms *species, site, diversity, species composition,* and *species richness*. The relationship between terms in the blue cluster in **Fig. 5** is reinforced by the fact that 44% of the scientific articles analyzed in this study addressed the topic of vegetation structure and phytosociological parameters. Particularly, the overriding importance of *species* recalls the strong, narrow focus or old paradigm of forest restoration in this structural level rather than on functions and processes (Stanturf et al. 2014a, b; Holl 2017).

2.5. FINAL CONSIDERATIONS

The Brazilian Amazon has undergone an accelerated process of forest loss and degradation initiated in the 1970s and that was promoted by the government to economically develop the region. Numerous incentives programs and infrastructure projects, such as the opening of large roads and mineral extraction, have ultimately resulted in the deforestation of ca. 20% (780,967 km^2) of the region. Deforestation has been reduced thanks to united actions of international governmental and non-governmental organizations and research institutions in the last few decades. Efforts to reverse deforestation have produced a list of critical municipalities where landowners can't receive rural credits for their activities and thus they are forced to work legally. However, there is still much illegal deforestation in the Brazilian Amazon (Brancalion et al. 2018), although in smaller proportion than before 2007 when critical municipalities were established. In that year, deforested land attained 11,500 km^2 and 716,978 km^2 (14%) of the region had already been deforested.

Forest restoration has used a number of techniques including –in descending order of importance- seedling planting, agroforestry systems, assisted natural regeneration and natural regeneration. We emphasize that each restoration action and technique must be adapted to the local reality with a well-defined objective. We compiled a list of 405 forest recovery projects since 1950 but were not able to estimate the amount of recovered area. Despite of numerous restoration projects spread out in the Brazilian Amazon, there is still a lack of scientific production in this field. From the in-depth knowledge of forest restoration as a science, it will be possible to propose better actions for future projects to recover deforested and degraded areas. There are numerous land use regulations and guidelines as well as legal obligations to restore forests, spanning from the municipal to the federal scales. It is though necessary more governmental attention to manage forest land, both to punish those who are degrading the environment and to audit those who are under a recovery program. Unfortunately, current Bolosonaro´s government is not working in that direction. We hope that the motivated complains in the scientific community and further action redresses this situation (Escobar 2019).

2.6. ACKNOWLEDGEMENTS

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SUPPORTING INFORMATION

Table S1 List of 12 universities and five major environment agencies that were surveyed for projects related to forest recovery areas in the Brazilian Amazon.

States	**University**
Acre	Federal University of Acre - UFAC (http://www.ufac.br/)
Amapá	Federal University of Amapá - UNIFAP (http://www.unifap.br/public/)
Amazonas	State University of Amazonas - UEA (http://www3.uea.edu.br/)
	Federal University of Amazonas - UFAM (https://ufam.edu.br/)
Pará	State University of Amapá - UEAP (http://ueap.edu.br/)
	State University of Pará - UEPA (http://www.uepa.br/)
	Federal University of Western Pará - UFOPA (http://www.ufopa.edu.br/ufopa)
	Federal University of Pará - UFPA (https://portal.ufpa.br/)
	Federal Rural University of Amazonia - UFRA (https://novo.ufra.edu.br/)
Rondônia	Federal University of Rondônia - UNIR (http://www.unir.br/)
Tocantins	State University of Tocantins - UNITINS (https://www.unitins.br/nPortal/)
	Federal University of Tocantins - UFT (http://ww2.uft.edu.br/)
Abbreviation	**Environmental Agencies**
CIFOR	Center for International Forestry Research - Centro Internacional de Pesquisas Florestais
ICMBio	Chico Mendes Institute for Biodiversity Conservation - Instituto Chico Mendes de Conservação da Biodiversidade
MMA	Ministry of the Environment - Ministério de Meio Ambiente
IBAMA	Brazilian Institute of the Environment and Renewable Natural Resources - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
SEMA	State Department of the Environment - Secretaria Estadual de Meio Ambiente

Table S2 Annual deforestation between 2007 and 2018 and total accumulated deforestation in the priority municipalities to combat and control deforestation and in the "successful" municipalities deemed with controlled deforestation in the Brazilian Amazon.

Municipalities/ States	Deforestation rates (km^2)													
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2018*	Situation
Apuí/Maranhão	94	71	64	46	49	75	86	80	107	162	170	162	2,622	To combat and control deforestation
Boca do Acre/ Maranhão	34	39	25	53	60	55	35	66	48	91	91	117	2,619	
Lábrea/ Maranhão	113	67	45	41	77	85	126	136	243	317	284	326	4,785	
Manicoré/ Maranhão	39	42	30	63	56	61	43	29	73	86	100	82	2,093	
Novo Aripuanã/ Maranhão	45	63	16	21	19	18	43	26	53	154	127	142	1,478	
Amarante do Maranhão/ Maranhão	27	61	60	13	16	7	12	12	9	7	8	7	2,342	
Grajaú/ Maranhão	73	56	59	90	51	43	23	22	11	9	9	7	1,506	
Aripuanã/ Mato Grosso	84	81	42	32	34	21	40	40	52	84	93	113	4,319	
Colniza/ Mato Grosso	257	125	76	79	87	81	156	146	251	224	176	239	4,970	
Cotriguaçu/ Mato Grosso	128	78	36	27	22	45	43	45	58	51	44	23	2,235	
Gaúcha do Norte/ Mato Grosso	69	198	9	3	10	10	25	32	11	58	48	9	3,712	
Juara/ Mato Grosso	117	125	31	15	58	16	16	28	46	39	18	19	8,053	
Juína/ Mato Grosso	45	54	21	10	8	14	27	33	52	52	33	23	4,567	
Marcelândia/ Mato Grosso	80	178	4	6	21	12	37	35	45	55	48	22	3,698	
Nova Bandeirantes/ Mato Grosso	141	126	53	17	49	34	63	70	37	82	49	62	3,477	
Nova Maringá/ Mato Grosso	17	18	11	6	9	5	44	36	41	24	49	42	3,313	
Paranaíta/ Mato Grosso	62	41	8	10	16	6	13	39	19	29	41	43	2,426	
Altamira/ Pará	369	341	391	196	238	230	296	294	309	410	225	435	9,162	
Anapu/ Pará	82	74	27	78	174	16	19	32	96	86	99	60	2,602	
Cumaru do Norte/ Pará	292	186	37	44	59	59	38	25	41	33	42	30	7,368	
Itaituba/ Pará	121	171	149	91	90	95	187	100	90	129	80	98	5,665	
Itupiranga/ Pará	131	228	90	52	60	43	63	48	28	88	30	33	4,913	
Marabá/ Pará	166	351	112	80	65	53	81	39	46	100	42	51	8,727	
Moju/ Pará	79	116	67	116	43	43	35	25	26	31	46	35	4,430	
Novo Progresso/ Pará	348	236	316	51	54	74	163	115	169	141	61	194	6,289	
Novo Repartimento/ Pará	361	482	289	224	183	121	150	78	74	224	122	173	8,127	
Pacajá/ Pará	168	261	101	275	185	34	30	78	166	141	180	138	5,927	
Placas/ Pará	63	86	40	56	40	80	25	53	89	68	88	93	2,283	
Portel/ Pará	87	97	31	56	68	12	17	60	109	178	168	100	2,176	
Rondon do Pará/ Pará	86	54	31	53	27	14	29	22	19	27	19	25	5,597	
São Félix do Xingu/ Pará	878	765	444	354	140	169	220	152	199	315	240	294	18,734	
Senador José Porfírio/ Pará	60	15	4	29	72	19	15	28	59	68	99	52	1,092	
Uruará/ Pará	154	92	100	70	39	53	47	15	53	64	89	85	3,489	

Buritis/ Rondônia	117	21	17	34	43	22	51	58	55	83	68	45	2,632	**To combat and control deforestation**
Candeias do Jamari/ Rondônia	49	49	13	13	18	18	48	41	48	98	107	104	2,258	
Cujubim/ Rondônia	69	49	31	35	48	57	55	41	66	86	87	73	1,944	
Machadinho D'oeste/ Rondônia	79	53	29	18	55	67	81	61	98	94	99	74	3,443	
Nova Mamoré/ Rondônia	139	67	29	61	78	78	134	137	149	147	180	152	3,895	
Pimenta Bueno/ Rondônia	44	43	14	4	4	33	6	4	7	10	23	20	2,483	
Porto Velho/ Rondônia	433	214	106	135	325	196	316	225	289	309	354	389	10,200	
Mucajaí/ Roraima	61	216	20	61	27	18	39	49	22	46	8	19	1,917	
Total	5,858	5,692	3,076	2,717	2,774	2,193	2,975	2,655	3,462	4,496	3,944	4,209	183,567	
Alta Floresta/ Mato Grosso	61	16	7	3	6	2	7	10	9	9	12	9	4,975	**Controlled deforestation**
Alto Boa Vista/ Mato Grosso	7	18	14	4	20	5	2	1	0	1	6	45	1,226	
Brasnorte/ Mato Grosso	50	117	16	12	13	10	12	16	31	27	25	15	4,444	
Cláudia/ Mato Grosso	4	27	25	8	12	4	19	22	21	14	31	51	1,721	
Confresa/ Mato Grosso	66	65	8	13	25	50	20	24	21	19	27	16	3,907	
Feliz Natal/ Mato Grosso	22	224	4	28	28	20	22	50	84	80	41	63	2,387	
Nova Ubiratã/ Mato Grosso	20	141	31	23	94	20	10	16	28	23	44	24	4,479	
Peixoto de Azevedo/ Mato Grosso	109	71	25	23	58	41	52	23	37	36	40	24	3,622	
Porto dos Gaúchos/ Mato Grosso	12	30	9	22	21	8	15	17	31	9	20	33	3,132	
Querência/ Mato Grosso	40	72	7	22	15	39	14	15	18	22	17	71	5,258	
Santa Carmem/ Mato Grosso	11	24	6	11	10	3	25	9	8	21	27	15	1,570	
São Félix do Araguaia/ Mato Grosso	41	210	18	6	19	17	16	23	21	6	7	33	4,553	
Tapurah/ Mato Grosso	7	11	7	14	21	4	16	33	19	7	20	35	2,109	
Vila Rica/ Mato Grosso	102	79	8	7	12	11	8	5	6	6	6	3	4,654	
Brasil Novo/ Pará	112	18	58	50	39	9	32	9	11	7	28	20	2,690	
Dom Eliseu/ Pará	67	54	41	37	25	30	10	6	7	7	6	11	3,500	
Paragominas/ Pará	92	66	121	68	36	18	31	20	24	20	20	18	8,792	
Santa Maria das Barreiras/ Pará	120	107	25	48	34	20	21	20	13	19	18	18	5,956	
Santana do Araguaia/ Pará	223	191	27	40	34	23	39	24	17	20	15	13	7,252	
Tailândia/ Pará	58	73	17	50	19	9	33	10	7	14	14	14	2,286	
Ulianópolis/ Pará	29	137	44	19	23	32	11	3	23	18	16	7	3,546	
Total	1,252	1750	517	507	562	373	413	354	434	382	439	536	82,058	

***Accumulated deforestation until 2018**	**Km²**	**%**
Deforestation in the 41 priority municipalities to combat and control deforestation	**4,156**	**56**
Deforestation in the 21 municipalities with controlled deforestation	**536**	**7**
Deforestation in the rest of (713) Brazilian Amazon municipalities	**2,693**	**37**
Total deforestation in the Brazilian Amazon (775 municipalities)	**7,385**	**100**

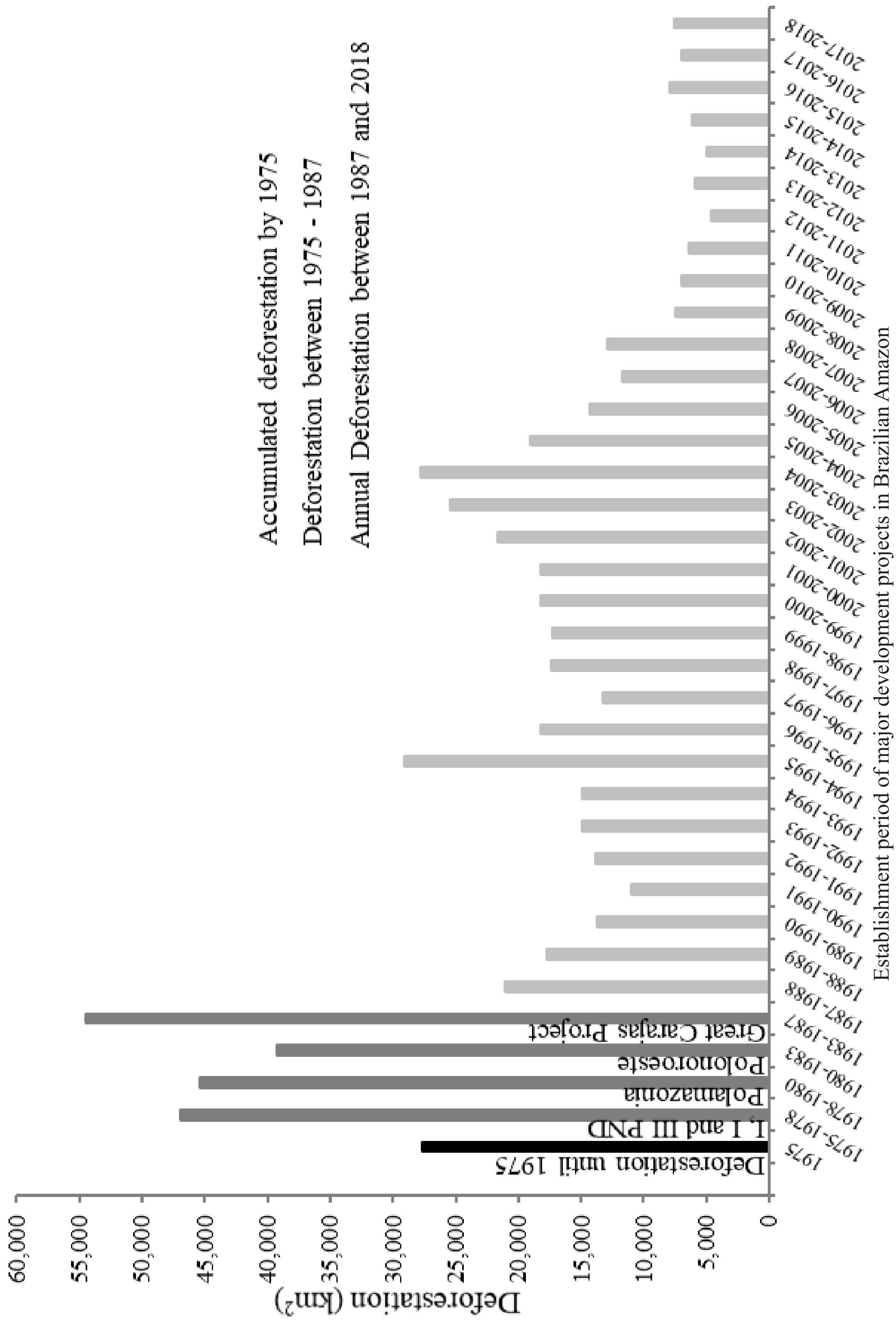

Fig. S1 Historical series of deforestation from 1975 to 2018 in the Brazilian Amazon.

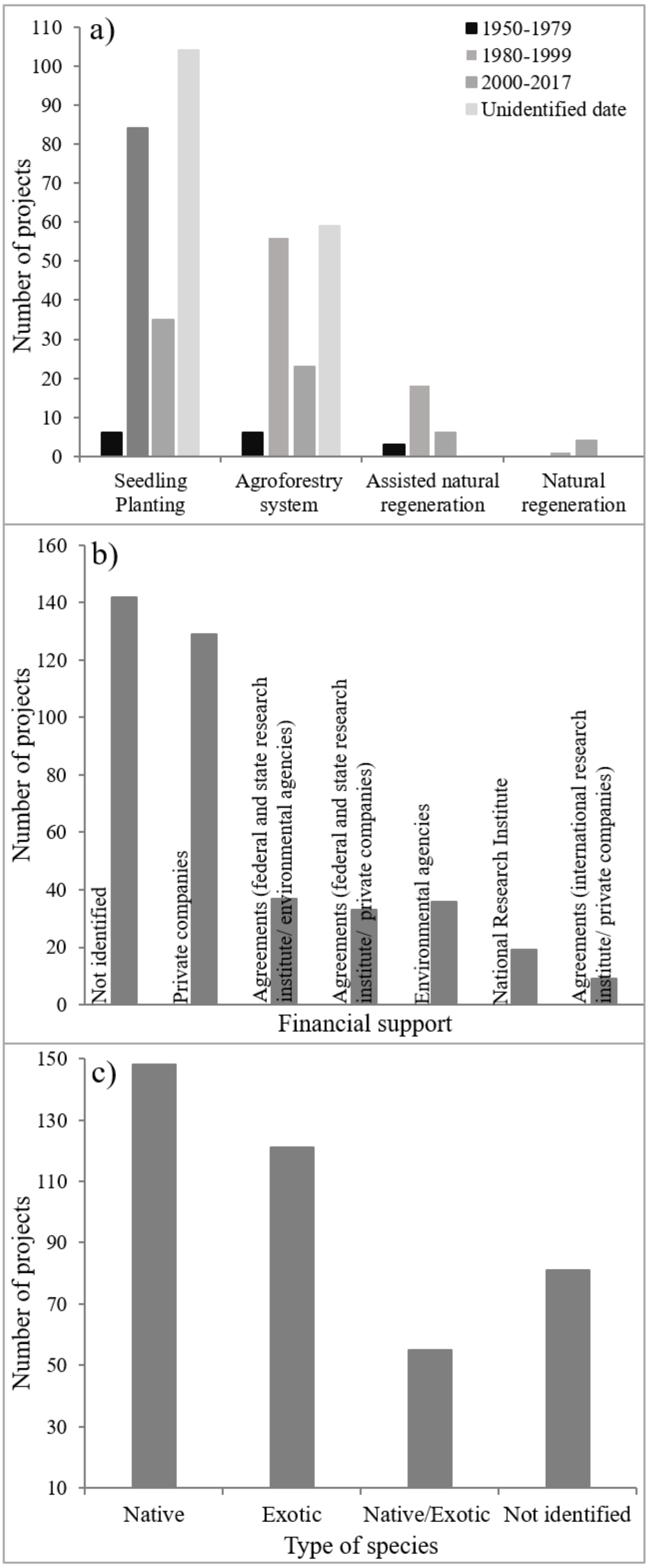

Fig. S2 Forest restoration projects implemented in Brazilian Amazon (1950 to 2017): a) types of technique; b) financial support, and c) type of species.

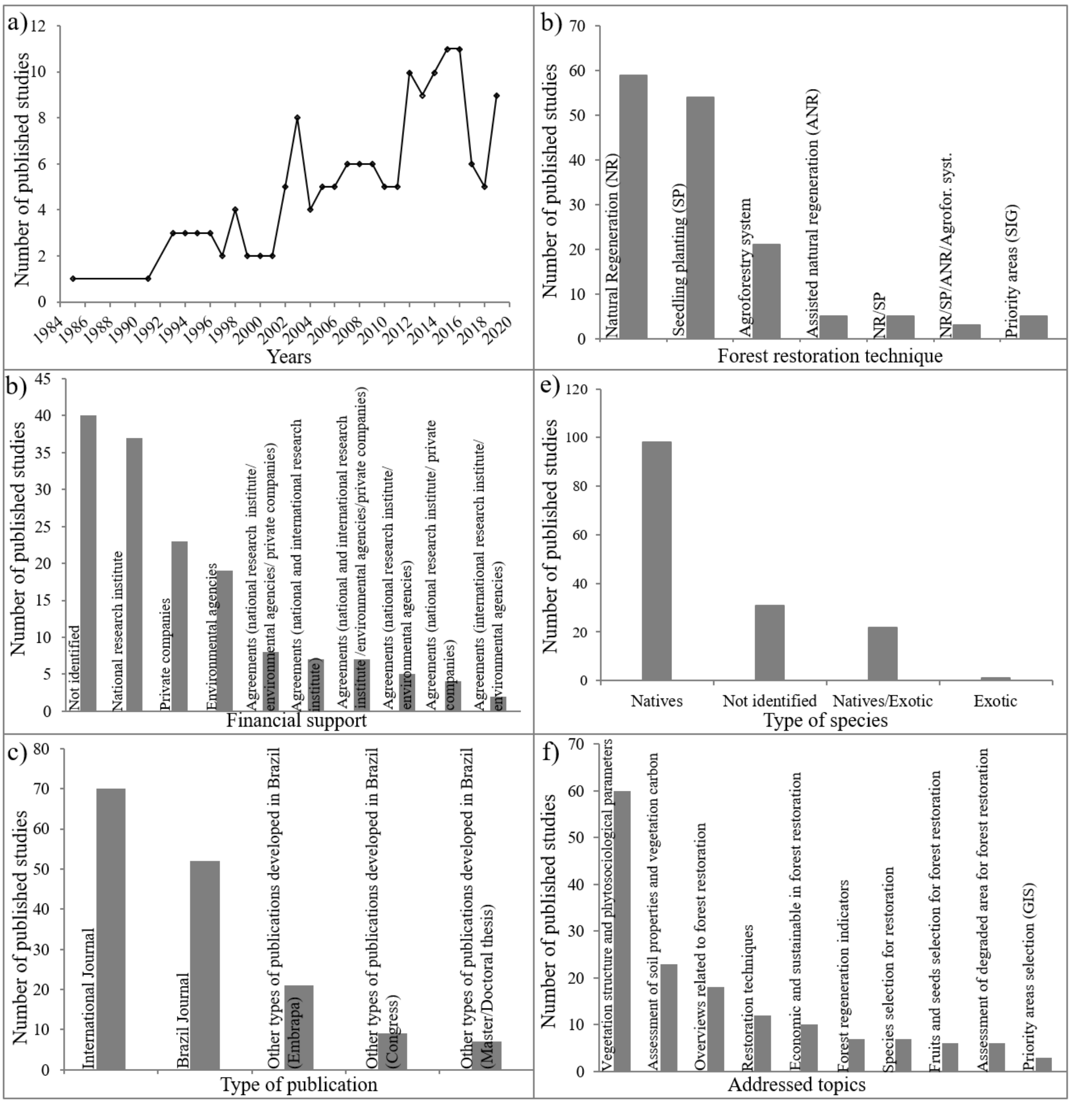

Fig. S3 Published studies related to forest restoration in the Brazilian Amazon: a) years of publication; b) financial support; c) type of publication; d) forest restoration techniques; e) type of species, and f) addressed topics.

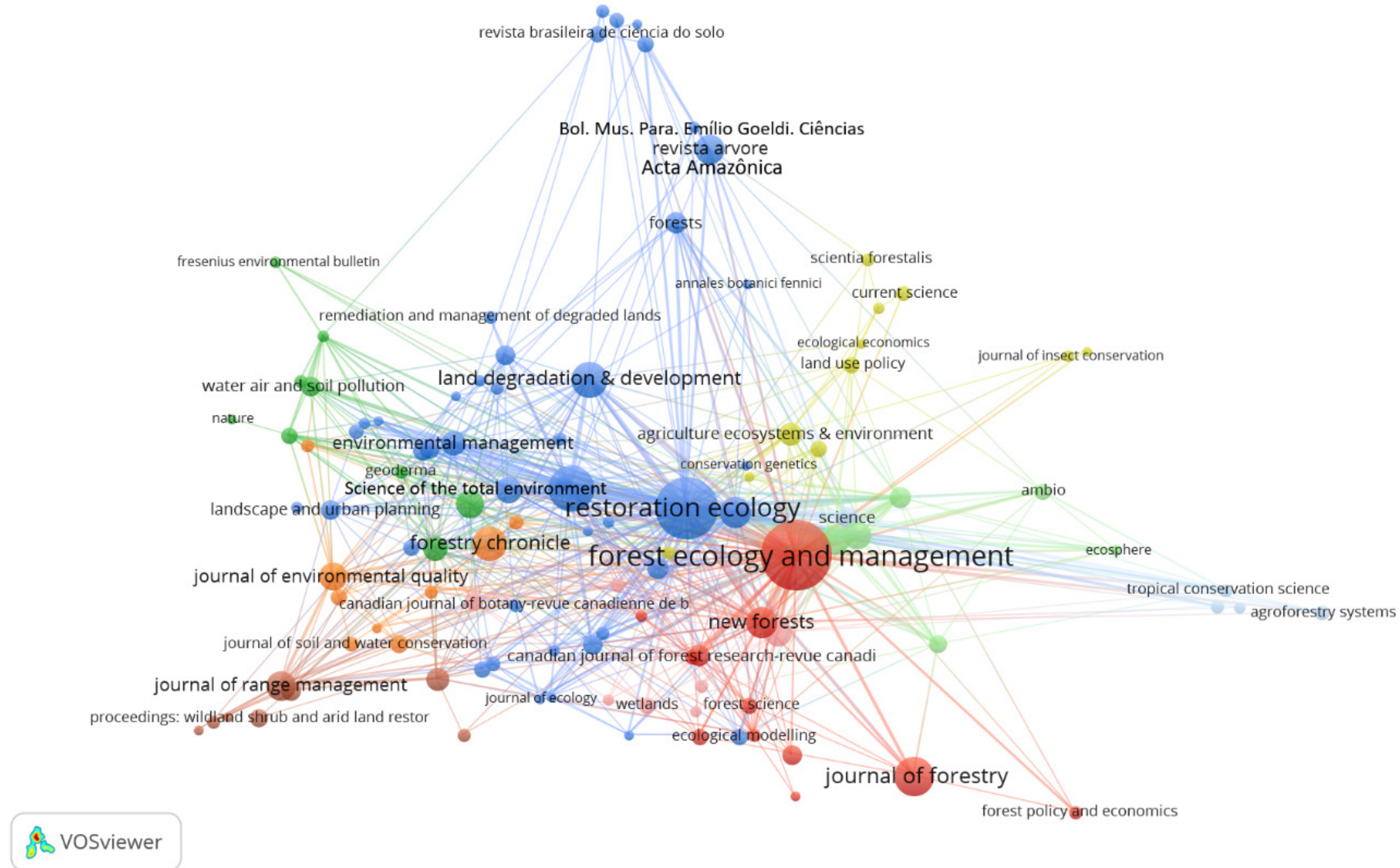

Fig. S4 Connectivity map of forest restoration studies in the Brazilian Amazon based on the journals where they were published. Frequency of studies is proportional to colored balls and font size.

Appendix S1

An overview for legal framework to conserve and restore forests in the Brazilian Amazon

After the deforestation “boom” in the Brazilian Amazon in the 1970s, the demand for forest restoration projects of degraded ecosystems increased, although many of them were unsuccessful (Rodrigues 2009). Thus, the need to establish norms and guidelines for environmental recovery emerged with the creation of legal instruments to compensate and repair damages caused to the environment.

The Brazilian Forest Code of 1934 (Decree 23,793/1934) was one of the first attempts to establish guidelines for the protection and maintenance of Brazilian forests as a common good for all. In 1965, it was reformulated to reinforce restriction to the use and occupation of land. In this reformulation (Federal Law no. 4,771/1965), the forest code has been criticized when dealing with limitations on the use of native forest in private properties, as found in art. 12: “*In planted forests not considered as permanent preservation, the extraction of firewood and other forest products or the manufacture of coal is permitted. In other forests, it will depend on the norm established in the act of the Federal or State Power (public), in obedience to the dictated prescriptions of the technique and the local particularities”.* Another notable reformulation in the Forest Code was Law No. 7,511/1986, which extends the limits of permanent preservation areas along the rivers or any watercourse. The 1988 Federative Constitution of Brazil empowered the Government to preserve and restore the essential ecological processes and to regulate the management of species and ecosystems, requiring that those who exploit mineral resources must recover the degraded environment. In the following year, the implementation of the Degraded Area Recovery Plan (*Plano de Recuperação de Área Degradada - PRAD*) was regulated with Decree No. 97,632, of April 1989.

With Law No. 9,605, of February 1998, those who cause damage to ecosystems should suffer penal and administrative sanctions derived from conducts and activities harmful to the environment. In Art. 23, II, the offender is required to recover the degraded environment, the Term of Conduct Adjustment (*Termo de Ajustamento de Conduta - TAC*) was also created with stipulated obligations, often translated into actions to recover degraded ecosystems.

The terms “restore” and “recover” have caused controversy in Brazil, and still brings doubts. For that reason, Law No. 9,985 of July 18, 2000, in art. 2, came up with the need to define the difference between “restored” and “recovered” ecosystems as follows: recovery is the restitution of a degraded ecosystem or wild population to a non-degraded condition, which may be different from its original condition; and restoration is the restitution of an ecosystem or a degraded wild population as close as possible to its original condition. The Permanent Preservation Area (PPA; *Área de Preservação Permanente - APP*) is a key issue for forest recovery. *CONAMA* - National Environment Council (Conselho Nacional de Meio Ambiente) Resolution No. 369, of March 28, 2006, established the legal duty of the land owner to recover the irregularly suppressed or occupied Permanent Preservation Areas, considering the due obligations to comply with the *PRAD*.

The Brazilian Institute for the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA*), by means of the Normative Instruction (*IN*) no.4 of April 4, 2011, established better procedures for *PRAD* elaboration. This IN distinguishes two types of *PRAD* (*PRAD* and simplified *PRAD)*, applied according to each case specified in the standards, and it is also determined that “*PRAD* must gather information, diagnoses, surveys and studies that enable evaluating the degradation and the consequent definition of measures suitable for the recovery of the area”.

The most recent change to the Forestry Code was Law No. 12,727/2012, also known as the Native Vegetation Protection Law (*Lei de Proteção da Vegetação Nativa - LPVN*), which establishes actions in several articles (1-amended, 7, 17, 41, 44, 46, 51, 54, 58, 61-amended, 64, 65 and 66) for the preservation and recovery of degraded areas in the Amazon and other Brazilian biomes.

Over the years, several legal frameworks have emerged with guidelines for implementing restoration projects (**Table S3** - List of laws, decrees, normative instructions and resolutions on the recovery of degraded areas in the Brazilian Amazon).

Table S3 List of laws, decrees, normative instructions and resolutions on forest recovery in the Brazilian Amazon, ordered in increasing year

Regulation instrument	Description	Government Level
Law no. 6,938, of 31/08/1981.	Its art. 2 aims to preserve, improve and recover the environmental quality in Brazil. CONAMA and SISNAMA - National System of the Environment (Sistema Nacional do Meio Ambiente) were created from this law.	Federal
Law no. 7,347, of 24/07/1985.	Created instruments to enable the recovery of degraded areas based on a bidding system through a specific fund.	Federal
Resolution no. 001, of 23/01/1986.	CONAMA Resolution, which establishes criteria and guidelines for the Environmental Impact Study (Estudo de Impacto Ambiental - EIA) and Environmental Impact Report (Relatório de Impacto Ambiental - RIMA).	Federal
Brazilian Constitution of 1988.	Its art. 225: Everyone has the right to an ecologically balanced environment. Par. 1 - It is incumbent upon the Government to: I - preserve and restore essential ecological processes and provide for the ecological management of species and ecosystems; Par. 2 - Anyone who exploits mineral resources is obligated to recover the degraded environment.	Federal
Decree no. 97,632, of 10/04/1989.	Regulated the law no. 6,938/81, forcing the recovery of a degraded area as part of the Environmental Impact Report. It instituted the Plan for the Recovery of Degraded Areas (Plano de Recuperação de Áreas Degradadas - PRAD).	Federal
Law no. 8,171, of 17/01/1991	Chapter VI - Protection of the Environment and Conservation of Natural Resources. The Government shall: (iv) promote and/or stimulate the recovery of areas in the process of desertification	Federal
Law no. 9,605, of 12/02/1998.	Provides criminal and administrative sanctions derived from harmful activities to the environment. Via art. 23, II, obliges the offender to restore the degraded environment.	Federal
Decree no. 3,420, of 20/04/2000.	Provides the creation of the National Forest Program (NFP). In its art. 2: [...] II - Foster reforestation activities, especially in small rural properties; III - Recover forests of permanent preservation, legal reserves and altered areas.	Federal
Law no. 9,985, of 18/07/2000.	In its art. 2, it distinguishes for its purposes a “recovered” ecosystem versus a “restored” ecosystem, as follows: [...] XIII - Recovery: restitution of a degraded ecosystem or wild population to a non-degraded condition, which may be different from its original condition; XIV - Restoration: restitution of a degraded ecosystem or wild population as close as possible to its original condition.	Federal
Resolution no. 302, of 20/03/2002.	Art. 2: III - Environmental Conservation Plan and Use of the Artificial Reservoir Environment: set of guidelines and propositions with the objective of disciplining conservation, recovery, use and occupation of the surroundings of artificial reservoirs.	Federal
Resolution no. 310, of 5/07/2002.	Art. 10: Sustainable Forest Management Plan, will only be approved: I - the proper registration, maintenance and recovery of the Legal Reserve; II - maintenance and recovery of Permanent Preservation Areas and other protected areas.	Federal
Decree no. 4,339, of 22/08/2002.	Establishes principles and guidelines for implementing the National Biodiversity Policy, with incentive mechanisms for the recovery and protection of PPA (APP) and legal reserves provided by Law.	Federal

Law no. 11,284, of 2/03/2006.	Provides for the management of public forests for sustainable production; and in its art. 31, it is incumbent upon the entrepreneur: IV - to recover the degraded areas, when their actions or omissions are identified.	Federal
Resolution no. 369, of 28/03/2006.	CONAMA Resolution, in its art. Paragraph 2 considers the legal duty of the owner or proprietor to recover irregularly suppressed or occupied PPAs (APPs). In Paragraph 8, those entitled with the activities of research and extraction of mineral substances in a PPA are also obliged to recover the degraded environment.	Federal
Resolution no. 387, of 27/12/2006.	CONEMA, provides for environmental recovery actions, through elaboration of the Settlement Recovery Plan, with recovery of legal reserve areas and permanent preservation.	Federal
Decree no. 6,514, of 22/07/2008.	Provides for infractions and administrative sanctions to the environment. In art. 2, any action or omission that violates the legal rules of use, enjoyment, promotion, protection and recovery of the environment is considered an environmental administrative infraction; and in art. 108, provides the embargo of work or irregular activity.	Federal
Decree no. 6,686, of 10/12/2008.	In its art. 17, the embargo of irregularly exploited areas and the objective of the Sustainable Forest Management Plan, does not exempt its holder of the execution of maintenance activities or forest recovery.	Federal
IN ICMBio no. 06 of 01/122009.	In its art. 3, according to this Normative Instruction (IN), a precautionary administrative measure capable of preventing the occurrence of new illicit acts may be applied. In art. 39, the embargo of work or activity and their respective areas. Art. 80, to verify the existence of damages to be repaired, forcing the violator to present the recovery project. Art. 88, charging of a fine by ICMBio. Article 112, provides requests for conversion of fines in preservation services.	Federal
Resolution no. 429, of 28/02/2011.	Provides for the methodology of recovering Permanent Preservation Areas - PPAs (APPs).	Federal
IN IBAMA no. 4, of 13/04/2011.	Establishes procedures for the elaboration of a Degraded Area Recovery Project (Projeto de Recuperação de Área Degradada – PRAD).	Federal
Law no. 12,651, of 25/05/2012.	Provides for the protection of native vegetation and replaces the Forest Code, outlined by several articles (1-A, 7, 17, 41, 44, 46, 51, 54, 58, 61-A, 64, 65 and 66) with organized actions between the public sector and civil society.	Federal
IN ICMBio no. 11, of 11/12/2014.	Establishes procedures for the elaboration, analysis, approval and follow-up of the implementation of a Degraded Area Recovery Project, for the purpose of complying with environmental legislation.	Federal
Decree no. 9,179, of 23/10/2017.	In its art. 140, considers the services of preservation, improvement and reestablishment of the environment, and recovery actions: a) degraded areas for biodiversity conservation; (b) essential ecological processes; c) native vegetation for protection; and d) recharge water supply areas.	Federal
IN ICMBio no. 2, of 02/19/2018.	Provides the procedures related to the conversion of simple fines into services of preservation, improvement and recovery of the environment quality within the Chico Mendes Institute.	Federal

Constitution of the State of Pará	Contains determinations on the recovery of degraded areas in the chapters: III - Agricultural, Agrarian and Land Property Policy, IV - Science and Technology and VI - Environment. Promulgated on October 5, 1989 and updated until the edition of Constitutional Amendment No. 51 of December 14, 2011.	State (Pará)
Constitution of Rondônia	It contains determinations related to the conservation and restoration of natural resources by their rational use in art. 181, subsection III. Promulgated on September 28, 1989 and updated until Constitutional Amendment No. 80/2012.	State (Rondônia)
Constitution of Tocantins	In its art. 103, establishes development guidelines to be followed: VI - the preservation, protection and environmental recovery of the cultural and urban heritage described in art. 110. paragraph 4 and art. 142 paragraph 4. Promulgated on October 10, 1989, with the amendments adopted by Constitutional Amendments Nos. 01/89 to 14/2003.	State (Tocantins)
Constitution of Amazonas	In its art. 174. V - Guide farmers on management techniques for soil recovery. Art. 219. IV - development of management techniques, reforestation with species appropriate to the characteristics of the region and recovery of degraded areas. Art. 230 X - to register, monitor and supervise the concessions of the right of research and exploitation of water and mineral resources, as well as the recovery of the degraded environment. Article 236, Par. 2 - those who use environmental resources are obligated, by law, to contribute to the monitoring, prevention and recovery programs. Published on 05.10.89, updated until Constitutional Amendment No. 96, of 24.03.2017.	State (Amazonas)
Constitution of Roraima	In its art. 32, provides for all matters within the competence of the State: IX - protection, recovery and incentive to preserve and conserve the environment; Art. 166. IV - require mining companies to recover the soil and reforestation in places where mining activities were performed. Promulgated on 12/31/1991, updated until the Constitutional Amendment of 28.08.2012	State (Roraima)
Constitution of Amapá	In its art. 95, provides for all matters of State competence, especially on protection, recovery and incentive to preserve the environment. Promulgated on December 20, 1991, updated until Constitutional Amendment No. 0056, of 03.05.2017.	State (Amapá)
Constitution of Acre	In its art. 206, paragraph 2: All that exploit mineral resources will obligatorily perform the recovery of the degraded environment, using the technique determined by the competent public organ, according to the form of the law. Text promulgated on October 3, 1989 and updated by Constitutional Amendment n. 19/2000.	State (Acre)
Constitution of Mato Grosso	In its art. 296, the State will apply 5% of that to invest in water resource projects, in the study of water pollution control, floods prevention, silting and recovery of degraded areas. In art. 339, 342 and art. 353 Scientific and Technological Policy shall take respect for human life and health, rational and non-predatory exploitation of natural resources, preservation and recovery of the environment as its principles. Promulgated on 10/10/1989, with the amendments adopted by constitutional amendments nº 01/1991 to 71/2014.	State (Mato Grosso)
Constitution of Maranhão	In its art. 199, proceed to conduct agricultural zoning and implement a policy of support for the preservation and recovery of forest on the slopes, pre-Amazonian Maranhão and protected forests of watersheds/courses. In Article 239, it has the duty to ensure its preservation and recovery for the benefit of present and future generations; and in art. 244, it is mandatory to recover native vegetation in protected areas by law. Define the criteria and methods of recovery and penalties for offenders. Enacted on October 5, 1989, Constitutional Amendment No. 069, of 02/12/2014.	State (Maranhão)

3. EVALUATION OF SOIL EROSION PROCESS AND CONSERVATION PRACTICES IN THE PARAGOMINAS-PA MUNICIPALITY (BRAZIL)

CHAPTER III

Evaluation of soil erosion process and conservation practices in the Paragominas-Pa municipality (Brazil)*

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ABSTRACT

Over the last decades, the natural environment has been degraded at a much greater speed than its resilience. Lack of knowledge about soil natural limitations and mismanagement can increase their degradation and nutrient losses by erosion. The objective of this study was to estimate and map soil vulnerability to erosion through the Universal Equation of Revised Soil Loss (RUSLE) and based on the ecodynamic concept of physical and biotic environment analysis, and finally to evaluate conservation practices in the municipality of Paragominas with the economic database of IBGE/SIDRA. In the two analyzed methods, the percentage of areas with low and high potential and erosivity estimation were similar. The estimation of low and low-moderate loss and vulnerability represents about 77% (15,064 km^2) of the territory by RUSLE and 60% (11,485 km^2), by ecodynamic concept. The high to very high soil loss zones represent only 3% (642 km^2) and 2.7% (584 km^2), in the RUSLE and ecodynamic concept, respectively. Most of the variables analyzed in both methods presented low estimation values of loss and erosivity potential. The soil and slope attributes, for example, obtained exactly 79% (15,377 km^2 - RUSLE) and 80% (15,572 km^2 - ecodynamic concept), except for the climate and factor R attributes, in both methods the vulnerability potential and erosion, were only 1.5% (292 km^2) and 1.3% (253 km^2), based on the ecodynamic concept and RUSLE respectively. The geospatial analysis of the use practices correlated with the economic data showed an intense use of agricultural activities, logging, and mining, which caused severe environmental damages, considering that 45% (8,773.3 km^2) of the municipality have already been deforested and converted into other uses. The municipality still has 47% (9,182 km^2) of its territory covered by altered primary vegetation and 23% (4,441 km^2) by secondary vegetation, important information to subsidize decision-making processes related to ecological-economic strategies for the management of natural resources in the study area.

Keyword: Agriculture, Environmental variables, Potential for soil loss, Amazon.

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3.1. INTRODUCTION

Erosion is a process by which soil and rocks wear out, then transported by natural or anthropogenic agents and deposited elsewhere (Verheijen *et al.*, 2009), it can pollute water, cause land degradation, reduce soil fertility and increase the loss of organic matter (Cerdan *et al.*, 2010). Changes in the management and use of land resulted from human activities can increase soil erosion causing irreversible damage to the environment (Fiorio *et al.*, 2016; da Silva *et al.*, 2016). The vegetation withdrawal due to the insertion of plantations can increase up to 600% of soil erosion (Chaplot *et al.*, 2005). Soil loss brings concern all over the planet, as it is a source for food production (Albuquerque *et al.*, 2005).

Production of food and other goods for human needs, combined with population growth and agricultural intensification, has resulted in severe land degradation and, particularly, soil erosion. Between 1961 and 2010 the world population duplicated from 3 billion to 6 billion inhabitants, while the crop production increased four times in almost the same area (FAO, 2017). It is estimated that since the beginning of stable agriculture, ca. 430 million hectares were damaged due to soil erosion (Lal, 2017).

Agricultural production in Brazil was fostered through a National Development Plan (PND, in Portuguese: Plano Nacional de Desenvolvimento) in the 1970s aiming to improve the country's economy (Becker, 2005). Such a plan was developed to attract entrepreneurs to the Brazilian Amazon, with the government releasing taxes on rural credits to incentivize investment (Kohlhepp, 2002). That period was marked by huge agricultural, industrial, and silvicultural projects besides infrastructure actions (Hall, 1989; Serra, 1998). The intense advance of the agricultural sector and the territory occupation was evident in many Amazon municipalities, leading to a drastic change in the landscape. For example, Paragominas has already 45% (8,773.3 km^2) of its land deforested (INPE, 2018), causing loss of soil organic matter and nutrients and soil erosion (Angima, 2003).

Lack of knowledge about soil limitations and inadequate soil management practices can trigger or speed up its erosion in agricultural areas (Navas *et al.*, 2005). Beyond land use activities, soil loss and degradation are affected by a combination of different environmental factors including geology (rock types), geomorphology (landform), vegetation (e.g. it's cover and structure), pedology (soil types), and climate (e.g. rainfall) (Arnesen, 2009). The awareness about risks to environment, economy, and livelihoods has resulted in research, technology, and production practices to minimize soil erosion (Bakker *et al.*, 2008).

Understanding and quantifying erosion processes are important steps in the decision making process regarding the best management to be adopted. Methods with empirical models are used, for example, the Universal Soil Loss Equation (USLE), which emerged in the late 1970s (Wischmeier & Smith, 1978) in the United States, but it is widely used in Brazil. This method presents great accuracy, as considers soil type, soil morphology, rainfall, cultivation practices, and management, allows quantification, and regionalization of the area with a higher risk of erosion (Wischmeier & Smith, 1978; Bertoni & Neto, 2005; 2012). It was later revised and adapted by several authors "Revised Universal Soil Loss Equation" (RUSLE). Another technique widely used to analyze the natural vulnerability to soil loss was based on the ecodynamic of Tricart (1977), modified by Crepani *et al.*, (2001), which uses the morphogenesis/pedogenesis relation integrated to satellite images, assigning values of vulnerability/stability to each thematic class.

The use of remote sensing and geographic information systems contribute significantly to monitoring, mapping, and managing landscapes (Ferreira, 2008), particularly in large and remote areas. For example, in Brazil where, besides having a huge territorial extension, access to some areas is also a constraint, which emphasizes the need for constant input in this field in order to monitor effectively. (Assad & Sane, 1998; Câmara *et al.*, 2001). The aim of this study is to estimate and map vulnerability to soil erosion through geospatial analysis (1), by a model of the Universal Equation of Soil Loss Revised (RUSLE) (a), and ecodynamic concept of analysis of physical and biotic environment (b), and evaluate the conservation practices (2), in Paragominas municipality in the Brazilian Amazon. We analyzed the local attributes of geology, geomorphology, vegetation, pedology, and climate, by means of satellite imagery analysis, thematic maps, and rainfall data, then a map of land was obtained which represents a range of levels of vulnerability to soil erosion. The analysis presented here can contribute to support decision makers regarding ecological-economic strategies for natural resource management in the study area and other parts of Brazilian Amazon.

3.2. MATERIAL AND METHODS

3.2.1. Study site

Paragominas municipality has an area of 19,465 km² and it is placed in Pará state, Brazil. Its original vegetation was mainly formed by dense ombrophilous forest (Watrin, 1992). The predominant soil type is yellow latosol, which is rich in clay and has low fertility. The climate is warm and humid, with an annual average temperature of 26.3 °C (**Fig. 1**).

3.2.2. Estimation and mapping of soil erosion

Soil erosion estimations were carried on the concept proposed by Tricart (1977), adapted by Crepani (2001) and by the Revised Universal Soil Loss Equation - RUSLE (Wischmeier & Smith, 1978). Both methods evaluate soil erosion with variables such as rainfall; soil type; land-use class; geology and geomorphology.

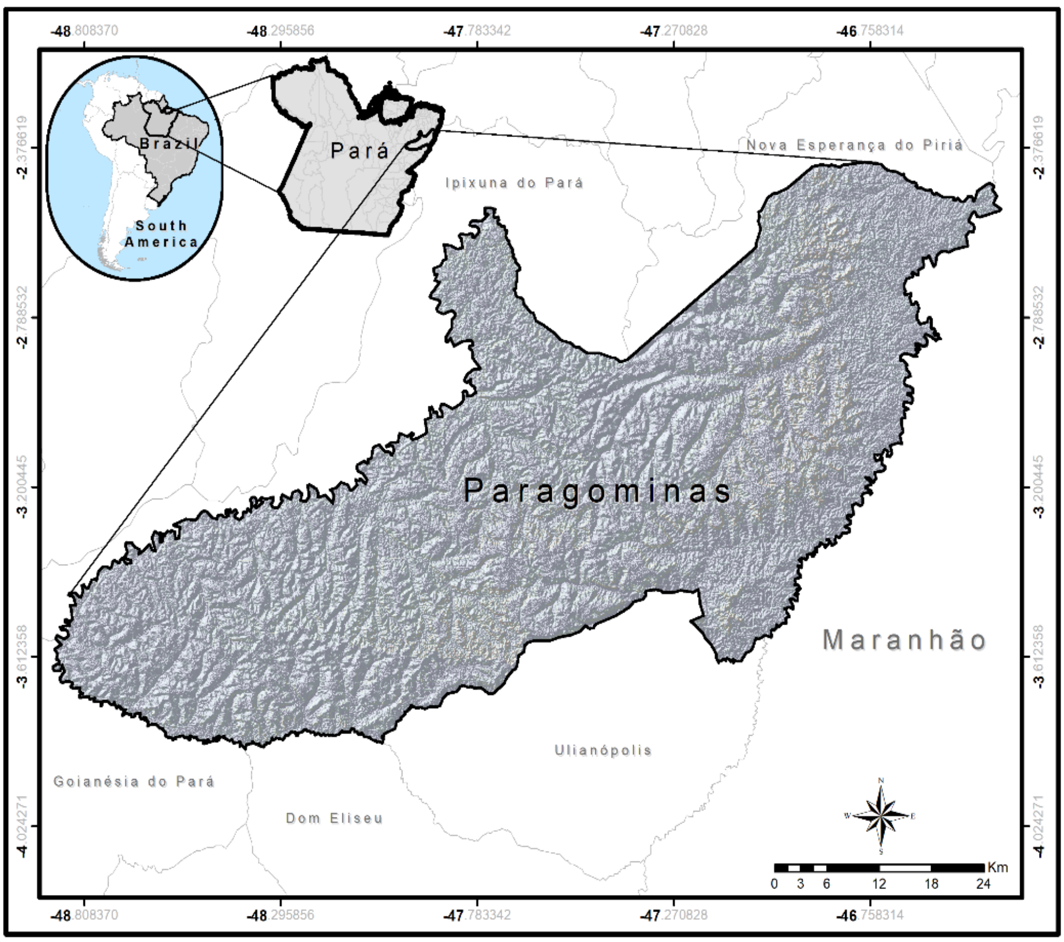


Fig.1. Paragominas municipality *(Elaborated by the authors)*.

2.3. Soil erosion based on the ecodynamic concept

We used the method based on the ecodynamic concept (Tricart, 1977), adapted by Crepani *et al.*, (2001) to Brazil. This concept considers the balance between soil formation processes (pedogenesis) and erosion processes (morphogenesis). It applies a range of soil erosion vulnerability values to the target land areas that are analyzed (stability or instability). Areas where pedogenesis and morphogenesis predominate have a value around 1 and 3, respectively, and areas where both processes are balanced have values around 2 (Table 1).

Table 1. Classes of soil erosion vulnerability.

Class	Vulnerability Value
Low Vulnerability	1 - 1.6
Low-moderate vulnerability	1.61 - 1.9
Moderate vulnerability	1.91 - 2.1
High-moderate vulnerability	2.2 - 2.4
High vulnerability	2.41 – 3

Source: Elaborated by the authors, adapted from Crepani *et al.*, (2001), by ecodynamic concept (Tricart, 1977).

Vulnerability values of soil erosion (between 1 and 3) were assigned based on attributes related to geology, geomorphology, pedology, vegetation types, and climate variables. They resulted in five thematic maps obtained through the Map Algebra of ArcGis 10.1 (Esri, 2012). For a given land area, the overall vulnerability (V) was:

$$V = G + SL + S + Vg + C / 5 \quad \textbf{(1)}$$

Where:

G = vulnerability due to Geology, SL = vulnerability due to Slope, S = vulnerability due to Soil, Vg = vulnerability due to Vegetation, and C= vulnerability due to Climate.

2.3.1 Geology attribute

Vulnerability due to Geology depends upon rock type. We used the geological database of the Brazilian Geological Service (CPRM, http://www.cprm.gov.br/), at a 1:100,000 spatial scale. The CPRM provides data in a georeferenced vector format of aerogeophysical projects available in Geobank (http://geobank.cprm.gov.br/). The values of soil erosion vulnerability related to rock types in the study area are reported in **Table 2**.

Table 2. Values of soil erosion vulnerability related to rock types.

Rock types	Value
Quartzites or metaquartzites	1.0
Rhyolite, granite, dacite	1.1
Granodiorite, quartz diorite, granulites	1.2
Migmatite, gneiss	1.3
Phonolite, nepheline syenite, trachyte, syenite	1.4
Andesite, diorite, basalt	1.5
Anorthosite, gabbro, peridotite	1.6
Mylonitos, muscovite quartz, biotite, shale chlorites	1.7
Pyroxene, kimberlite amphibolite, dunite	1.8
Hornblende, tremolite, shale actinolite	1.9
Shale staurolite, granatiferous shale	2.0
Phyllite, metassiltite	2.1
Slate, metargilite	2.2
Marbles	2.3
Quartz sandstone or orthoquartzites	2.4
Conglomerates, subgraywacke	2.5
Greywackes, arkose	2.6
Siltstones, mudstones	2.7
Husk	2.8
Calcareous, dolomites, marls, evaporites	2.9
Soft-bottom sediments: alluvium, colluvium, Sands, etc.	3.0

Source: Elaborated by the authors, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

3.2.3.2. Slope attribute

The source of soil erosion vulnerability related to the slope was adapted by Crepani *et al.*, (2001) study (Table 3). These data derive from SRTM (Shuttle Radar Topography Mission) available on EMBRAPA (Brazilian Corporation of Agricultural Research, (https://www.embrapa.br/territorial/), calculated using the ArcGis 10.1 slope tool.

Table 3. Values of soil erosion vulnerability related to slope.

Degree	%	Value/ Vuln.	Degree	%	Value/ Vuln.	Degree	%	Value/ Vuln.
<2	<3.5	1.0	9.9-11.2	17.4-19.8	1.7	19.1-20.4	34.6 - 37.2	2.4
2-3.3	3.5-5.8	1.1	11.2-12.5	19.8-22.2	1.8	20.4-21.7	37.2 - 39.8	2.5
3.3-4.6	5.8-8.2	1.2	12.5-13.8	22.2-24.5	1.9	21.7-23.0	39.8 - 42.4	2.6
4.6-5.9	8.2-10.3	1.3	13.8-15.2	24.5-27.2	2.0	23.0-24.4	42.4 - 45.3	2.7
5.9-7.3	10.3-12.9	1.4	15.2-16.5	27.2-29.6	2.1	24.4-25.7	45.3 - 48.1	2.8
7.3-8.6	12.9-15.1	1.5	16.5-17.8	29.6-32.1	2.2	25.7-27	48.1 – 50	2.9
8.6-9.9	15.1-17.4	1.6	17.8-19.1	32.1-34.6	2.3	>27	>50	3.0

Source: Elaborated by the authors, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

3.2.3.3. Pedology attribute

The vulnerability related to the pedology attribute (Table 4) refers to the mapping of soil units according to Crepani *et al.*, (2001), updated with Prado (2001) nomenclature. This attribute database was obtained from IBGE (Brazilian Institute of Geography and Statistics), based on the new Brazilian System of Soil Classification (EMBRAPA, 1999).

Table 4. Soil erosion vulnerability values related to soil types.

Soil Classes	Vuln.	Soil classes	Vuln.
Yellow latosol	1	Spodosol	2
Red-yellow latosol	1	Neosol litólicos	3
Red latosol	1	Neossolos flúvicos	3
Latosol brunos	1	Neossolos regolíticos	3
Latosol (...) humic	1	Neossolos quartzarênicos	3
Latosol bruno (...) humic	1	Vertisol	3
Acrisol	2	Organosols	3
Acrisol luvisol alisol nitosol	2	Gleysol	3
Acrisol nitosol	2	Gleysols plinthosol	3
Luvisol	2	Plinthosol	3
Chernozem	2	Rocky outcrop	3
Planosol	2	-	-

Source: Elaborated by the author, adapted from Crepani *et al.*, (2001), with new nomenclature from Prado (2001).

3.2.3.4. Vegetation and use of class attribute

The definition of values on vulnerability to erosion regarding vegetation attribute was identified under the forest canopy density using satellite imagery determined 21 class units, following the Crepani *et al.*, (2001) definition **(Table 5).**

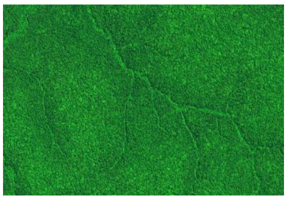
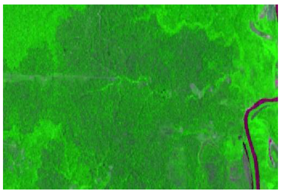
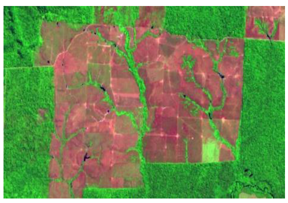
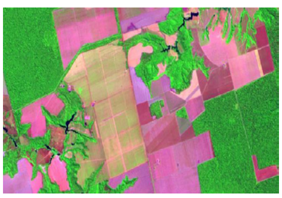
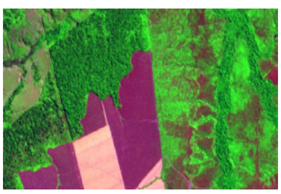
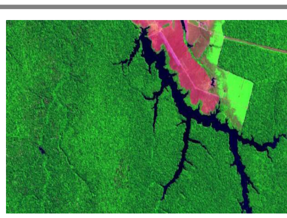
Table 5. Soil erosion vulnerability values related to vegetation types.

Vegetation Class	Vuln.
Dense ombrophilous forest	1.0
Open ombrophilous forest	1.0
Mixed ombrophilous forest	1.0
Semideciduous seasonal forest	1.4 - 1.7
Campinaranas formation	1.4 - 1.7
Forested savanna and steppe savanna	1.4 - 1.7
Dense tree steppe, with or without palms	1.4 - 1.7
Wooded savanna and steppe savanna da e wooded steppe Savanna	2.0
Decidual seasonal forest	2.0
Wooded campinarana	2.0
Wooded steppe	2.0
Buritizal with fluvial and/ or lake influence	2.0
Wooded campinarana with or without palms	2.4 - 2.6
Savanna park, wooded savanna park	2.4 - 2.6
Campinarana and steppe with shrub size	2.4 - 2.6
Vegetation under marine influence (sandbanks)	2.4 - 2.6
Vegetation under fluvial and/or lake influence	2.4 - 2.6
Montane refuge and high montane refuge	2.4 - 26
Woody- grassy savanna, woody-grassy steppe savanna, and Woody-grassy steppe	3.0
Woody-grassy campinarana	3.0
Vegetation under herbaceous marine influence	3.0
Montano and high-montano refuges	3.0
Cloud/ shadow/ exposed soil/ sparse vegetation	3.0

Source: Elaborated by the authors, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

It was used satellite imagery from Landsat 8 TM, orbits/points 222/62, 222/63, 223/62, and 223/63 (2015 data), with the lowest cloud coverage of the period, available in the website Glovis from NASA. From this satellite imageries, were produced a classification using the supervised Maximum Likelihood method. This method uses mean and variance of the data set for the classification decision rule, and for this reason, a considerable number of pixels are required for each region to be classified. First, the use class was defined, then samples (ROI's) of the areas to be classified in the image were generated (**Table 6**). With the selected ROI's for use class, the image was classified using the software ENVI 4.7, afterward, vulnerability values of classes were set as follows in **Table 7**.

Table 6. Land use patterns and Vegetal cover used in the satellite image classification.

Typological classification	Pattern identified in satellite image	Description
Primary Forest		Forests that have passed through interventions in the past, but have their primary structure conserved.
Secondary Forest		Forests that have undergone deforestation or degradation processes and are currently in regeneration.
Pasture		Livestock pasture areas with low biomass characterized areas with healthy pastures and degraded pastures.
Agriculture		Agricultural plantations mechanized, which presupposes high technological level and family agriculture areas.
Deforestation		Areas in which all vegetation cover was removed, leaving the soil exposed.
Urban area		Areas of urban agglomeration, with industrial estates, streets, buildings, and highways.
Hydrography		Drainage with rivers and springs.

Source: Elaborated by the authors.

Table 7. Soil Vulnerability regarding vegetation.

LANDSCAPE UNITES	AVERAGE			DEGREE OF VULNERABILITY	DEGREE OF SATURATION			
					RED	GREEN	BLUE	COLORS
U1	↑	3.0		VULNERABLE	255	0	0	
U2		2.9			255	51	0	
U3		2.8			255	102	0	
U4		2.7			255	153	0	
U5	V	2.6			255	204	0	
U6	U	2.5		MODERATE VULNERABILITY	255	255	0	
U7	L	2.4	S		204	255	0	
U8	N	2.3	T		153	255	0	
U9	E	2.2	A		102	255	0	
U10	R	2.1	B	MEDIUM STABLE VULNERABILITY	51	255	0	
U11	A	2.0	I		0	255	0	
U12	B	1.9	L		0	255	51	
U13	I	1.8	I		0	255	102	
U14	L	1.7	T		0	255	153	
U15	I	1.6	Y	MODERATE STABLE	0	255	204	
U16	T	1.5			0	255	255	
U17	Y	1.4			0	204	255	
U18		1.3			0	153	255	
U19		1.2		STABLE	0	102	255	
U20		1.1			0	51	255	
U21		1.0	↓		0	0	255	

Source: Vulnerability values of classes by image classification, adapted from Crepani *et al.*, (2001), by ecodynamic concept (Elaborated by the authors)

3.2.3.5. Climate attribute

About the attribute climate (pluviometry), 21 classes were classified on soil erosion (**Table 8**). The areas with lower annual pluviometric rate and higher extension of the rainy season were classified with values around stability (1.0) to intermediary values of vulnerability/stability (2.0). On the other hand, areas with higher annual pluviosity rates and shorter rainy season vulnerability presented values around 3.0.

In order to assign the vulnerability values to the climate, the precipitation data of the last 18 years of the municipality station, was used in the system of the national meteorological institute (INMET - http://www.inmet.gov.br/portal/). The average precipitation was calculated between January 2000 and November 2018 (**Fig. 2**).

Table 8. Soil vulnerability regarding pluviometric rate.

Pluviometric Intensity mm/ month	Vuln.	Pluviometric Intensity mm/ month	Vuln.	Pluviometric Intensity mm/ month	Vuln.
< 0 50	1.0	200 - 225	1.7	375 - 400	2.4
50 – 75	1.1	225 - 250	1.8	400 - 425	2.5
75 - 100	1.2	250 - 275	1.9	425 - 450	2.6
100 - 125	1.3	275 - 300	2.0	450 - 475	2.7
125 - 150	1.4	300 - 325	2.1	475 - 500	2.8
150 - 175	1.5	325 - 350	2.2	500 - 525	2.9
175 - 200	1.6	350 - 375	2.3	> 525	3.0

Source: Elaborated by the authors, adapted from Crepani *et al.*, (2001), by ecodynamic concept.

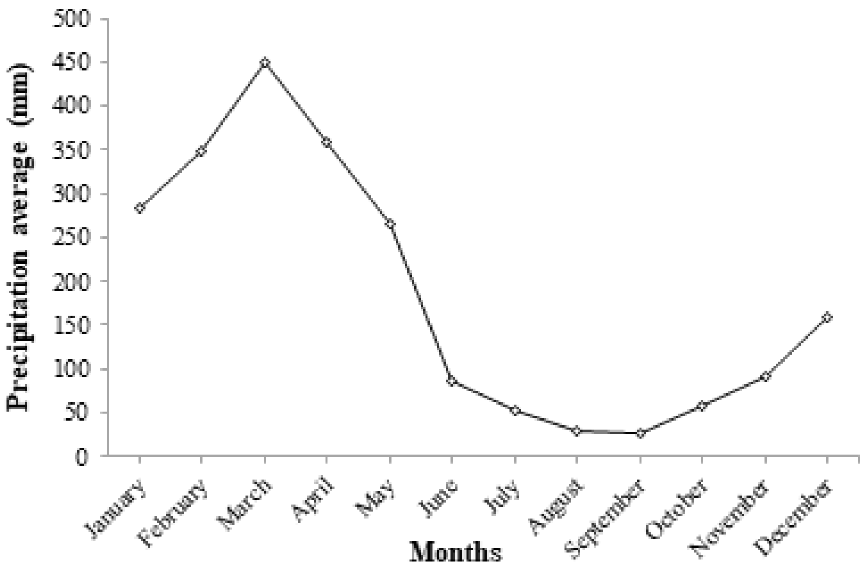


Fig. 2. Precipitation average from 2000 to 2018, INMET data. (*Elaborated by the authors*).

3.2.4. Revised Universal Soil Loss Equation (RUSLE) method.

Through the RUSLE equation, the main spatial distribution factors responsible for soil erosion were performed in the GIS environment. Information plans were embedded into the database and manipulated through the geoprocessing tools in ArcGis (**Fig. 3**).

$$A = R*K*L.S*C.P \tag{2}$$

Being: A = Soil loss calculated per unit area, ($Mg.ha^{-1}.ano^{-1}$); R = Rainfall factor: rainfall erosion index, ($Mg.ha^{1}.ano^{1}$); K = soil erodibility factor (MJ/ha.mm/h); L = slope length factor, (m); S = Slope degree factor, (%); C = Use and management factor (dimensionless); P = Conservationist practice factor (dimensionless).

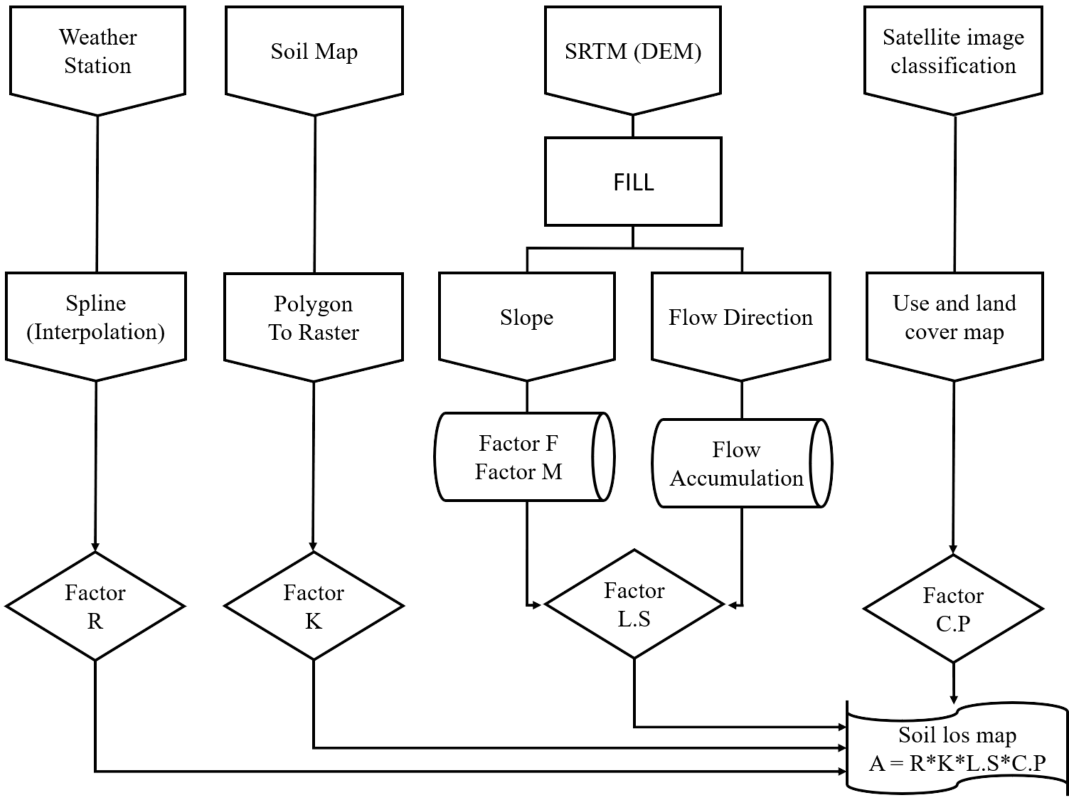


Fig. 3. Flowchart of the technique used in the generation of the soil loss map *(Elaborated by the authors).*

3.2.4.1. Factor R (Erosivity by rains)

In order to determine the annual rainfall erosivity, annual average precipitation data of the 28 rainfall stations contained in Paragominas were used for the period from 2000 to 2018. **Fig. 2** shows the monthly average rainfall erosivity using the formula used in Amazon:

(3)

$$EI_{monthly} = 42,307\ (Pm^2/Pa) + 42,77$$

Where: Pm = monthly precipitation and; Pa = annual precipitation average.

The average annual rainfall erosivity is obtained by the sum of the monthly erosivity average of each season. The map was generated in the ArcGis environment, by inserting the table (dbase format) with the spatial distribution of the stations (UTM coordinates of the stations) and their respective values of calculated erosivity. The interpolation of the values representing the spatial variation of erosivity was done through the ArcGis Spline tool.

3.2.4.2. Factor K (Soil Erodibility)

The evaluation of soil erodibility was obtained from IBGE Geoscience Center (Brazilian Institute of Geography and Statistics) in scale 1:5,000,000, based on the new Brazilian System of Soil Classification (EMBRAPA, 1999). The soil classes were grouped, generating a map of soil types, where the value of K was associated with each type.

3.2.4.3. Factor L.S (Topographic factor)

In this factor, the length of slope L represents the distance between the point which originates the surface flow to the point where the slope decreases enough for sediment deposition to occur. The slope gradient (S) refers to slope variation in slope intervals, these two parameters (L.S) are represented as a single topographic factor, defined as the rate of soil loss per unit area of a standard plot of 22.13 m in length and 9% of slope (Wischmeier & Smith, 1978). Calculated through the following steps:

$$F = \frac{\sin\beta / 0.0896}{3(\sin\beta)^{0.8} + 0.56} \qquad m = \frac{F}{(1+F)} \qquad L = \left(\frac{\lambda}{22.13}\right)^{m}$$

$$S_{(i,j)} = \begin{cases} 10{,}8 \sin\beta\,(i,j) + 0{,}03 & \tan\beta\,(i,j) < 0{,}09 \\ 16{,}8 \sin\beta\,(i,j) + 0{,}5 & \tan\beta\,(i,j) < 0{,}09 \end{cases}$$

In factor L the λ is the slope length, m the slope length exponent, and β the slope angle. The slope length is defined as the horizontal distance from which originates the surface flow to the point where the deposition begins or where the flow flows into a channel, and at factor S the angle β is taken as the mean angle of all sub-networks in the steepest direction (**Fig. 4**).

3.2.4.4. Factor C (Use/soil management) and P (Conservationists practices)

Factor C is the expected relationship between the soil loss of cultivated land under given conditions and the corresponding losses of land kept continuously uncovered and cultivated (Bertoni & Neto, 2005). While the factor P is the relationship between losses in soils with a given conservationist practice and those where the crop is planted in the slope direction.

A factor P of 0.01 was considered for areas with primary, secondary, and urban vegetation, 0.09 for agriculture, 0.45 for pasture, 1 for deforestation, and 0 for water. To elaborate the map of factor C, it was necessary to classify the satellite image for soil use and to assign C and P values for each type of use (Donzelli *et al.*, 1992), then convert to a raster format, where CP = C.P and CP factor specializations were obtained from the numerical reclassification of the vegetation cover and land use maps (Table 1) for the year 2017.

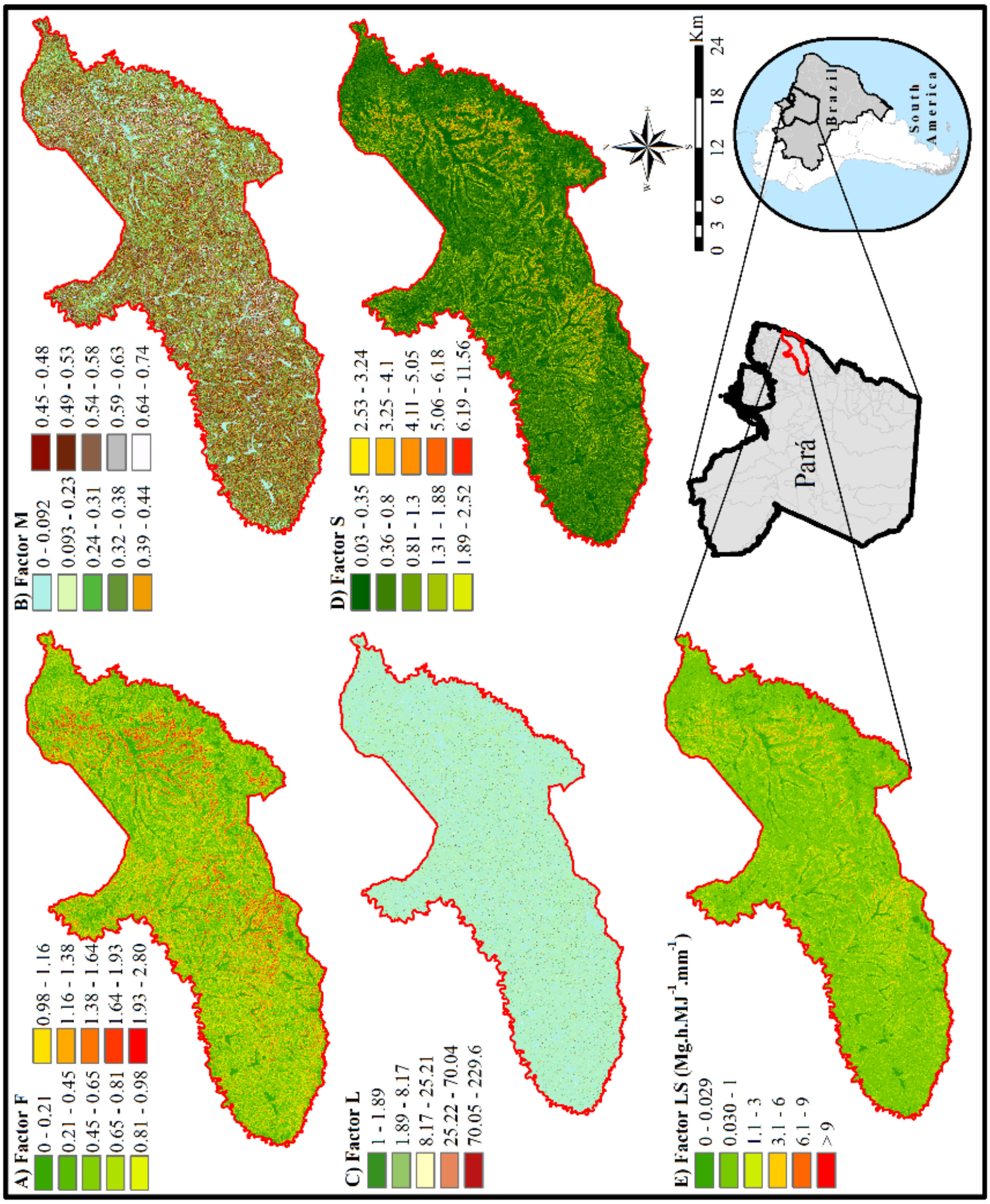


Fig. 4. Erosivity factors for the L.S calculation, based on A) Factor F; B) Factor M; C) Factor L, and D) Factor S. (*Elaborated by the authors*).

3.2.5 Conservation management and Practices

In order to evaluate the activities developed in Paragominas, mapping was carried out on the land use, a classification carried out by the TerraClass Project, then developed and executed by the Regional Center of the Amazon (CRA). The database of this project is the mapped deforested areas published by the PRODES Project - Monitoring of the Amazon Forest by Satellite.

TerraClass analyzes the possible causes of tree cutting considering the following classes: annual agriculture; unobserved area; urban area; mining; occupation mosaic; pasture with soil exposed; clean pasture; dirty grass; regeneration with grass; reforestation; secondary vegetation; forest and not-forest. This mapping counts a series of 10 years analysis of use and coverage (2004, 2008, 2010, 2012, and 2014), and to evaluate the current situation an unsupervised classification was performed in an image from 2017, described in **Table 6.**

To analyze the use and coverage of the soil obtained by the classifications carried out by satellite images, we also used the database of the IBGE Automatic Recovery System - SIDRA. This system has an economic historical series of data since 1974, in this component we analyzed only the years of 2004, 2008, 2010, 2012, 2014, and 2017. Another important practice developed in Paragominas is mining and to evaluate this component, it was used data from the National Department of Mineral Production (DNPM), available through the Geographic Information System of Mining – SIGMINE.

3.3. RESULTS AND DISCUSSION

After analysis, for the entire area of Paragominas municipality, a map with values of vulnerability to soil erosion was obtained for each following category: geology, slope, pedology, vegetation, and climate. Then, a general map of vulnerability to soil erosion and estimates of soil loss was created, according to the method of ecodynamics proposed by Tricart (1977) and adapted by Crepani *et al.*, (2001), and by RUSLE.

3.3.1. Analysis of the vulnerability based on the ecodynamic concept

3.3.1.1. Geology attribute

The basic information of geology is the cohesion degree of integrated rocks from the ecodynamics (Tricart, 1977). It means that in the most cohesive rocks the processes of weathering and pedogenic formation prevailed, while the less cohesive rocks are more susceptible to erosive processes. It is considered that in rocks with little cohesion erosive processes can prevail, while in very cohesive rocks the processes of weathering and soil formation must prevail (Crepani *et al.*, 2001). For this attribute, it was identified that only 1% (212 km^2) of the municipality area has low vulnerability to erosion, with rocks of granite, granodiorite, gneiss, and schist, with a value between 1.1 to 1.3 these rocks are more weather resistant (Gomes, 2006), since the igneous rocks are more resistant to temperature rises.

Paragominas municipality presents ca. 61% (11,874 km²) of its territory in the moderate-high attribute class (value 2.5) with sedimentary rocks of the sandstone, argillite, and silt types. This material can be composed of angular grains to sub-rounded enveloped by a clay matrix of infiltration (Frostick, 1984), which can lead to a greater erosive process. In 38% (7,397 km²) of the municipality area, there is a high vulnerability to soil erosion (value 3). These sediments have smaller interfluves (of higher-intensity dissection), for this reason, they receive vulnerability value higher for the geology attribute (Crepani, *et al.*, 2001) (**Fig. 5 A**).

3.3.1.2. Declivity attribute

The declivity is the relief slope regarding the horizon that has a direct relation with transformation speed from potential to kinetic energy. Thus, the higher the slope the faster the potential energy of rainwater becomes kinetic energy and higher the water masses velocity and their transport capacity, responsible for relief erosion (Watson & Laflen, 1986). Concerning respect to this attribute, it was verified that 46% (8,954 km²) of the municipality has declivity lower than 2% (value 1). In 34% (6,618 km²) of the municipality, the slope is between 2% and 6%, with low-moderate vulnerability (value 1.5). The regions presenting a slope between 6% and 20% represent 13% (2,530 km²) of Paragominas, moderate vulnerability value. Lang *et al.*, (1984) observed that zones with 9% of slope presented greater erosion between furrows of topsoil compared to an area of 3% slope.

Paragominas is located in the morphostructural domain of plateaus in non-folded sedimentary sequences (IBGE, 1996), characterized by flattened structural surfaces, with an average altitude of around 200 m. For this reason, only 5% (973 km²) of the municipality has a slope between 20% and 50% (moderate-high vulnerability), so regions having a slope higher than 50% (high vulnerability) correspond to only 2% (289 km²) of the total area (**Fig. 5 B**).

3.3.1.3. Soil attribute

Approximately 79% (15,337 km²) of Paragominas soil is composed of latosols, which are mineral soils, deep, well-drained, with B horizon latosolic, usually cohesive, quite hard when dry, mainly in the AB and BA horizons (Rodrigues *et al.*, 1991; Embrapa, 1999). Therefore, there are more stable soils and resistant soils to erosive processes with value 1 of vulnerability. Only 2% (389 km²) of its territory has argisol soils (vulnerability value 2) since their soils are moderately stable with erosive processes. This type of soil has a different textural gradient between A and B horizons, this can lead to soil loss by difficulty in infiltration,

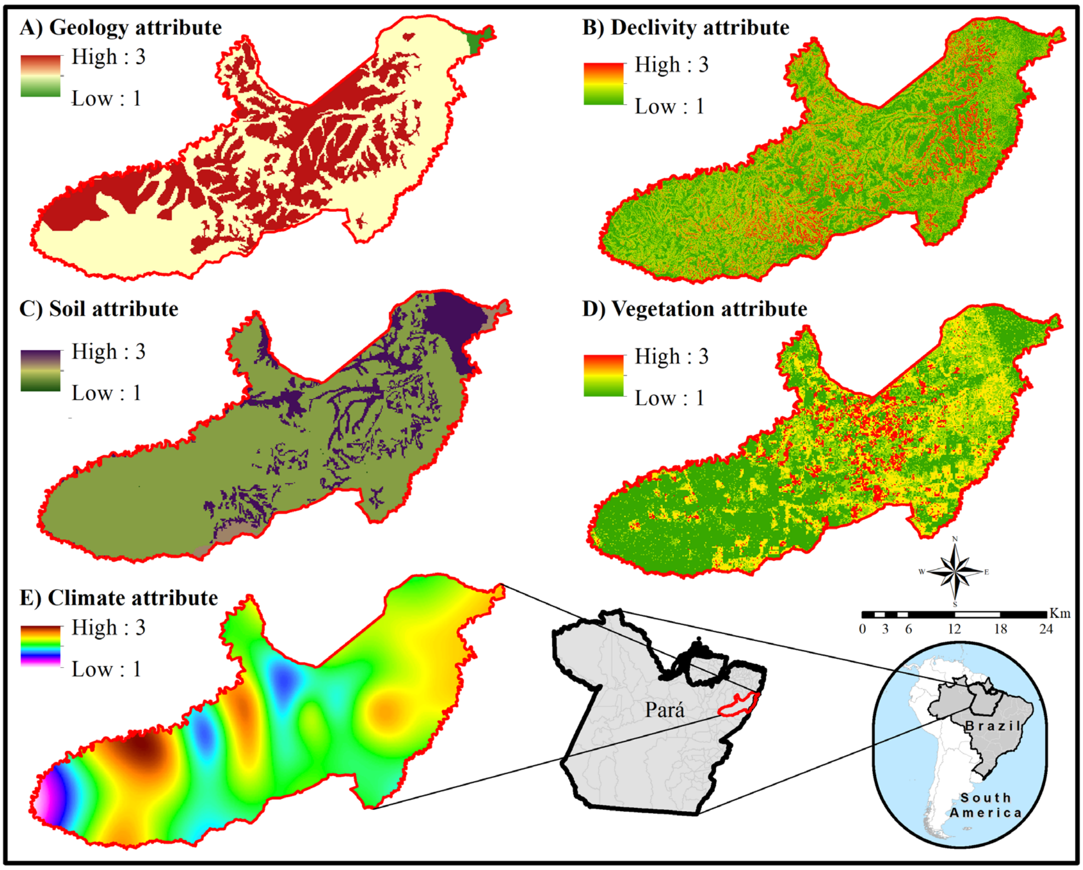


Fig. 5. Map of attributes responsible for vulnerability to soil erosion, based on A) Geology attribute; B) Declivity attribute; C) Soil attribute; D) Vegetation attribute, and E) Climate attribute *(Elaborated by the authors)*.

Schaefer *et al.*, (2002), in their study identified nutrients losses by erosion on simulated rainfall conditions, with different surface coverages on argisol soils.

The vulnerable soil erosion (vulnerability value 3) of the municipality corresponded to the regions with gleysol and plintosol representing 2% and 17% (3,698 km²), respectively (**Fig. 5 C**). The plintosols, for example, are mineral soils formed through water percolation restriction. These soils are poorly drained with excessive plinization (Rodrigues, 2003), while gleysol is characterized by high gley status of soils, which results in a reduced moisture regime whereby soil waterlogging for a long period during the year (Embrapa, 1999).

3.3.1.4. Vegetation attribute (Soil use)

The composition and structure of the vegetation are important components in soil loss analyzes (Gomes, 2006). Deforestation is one of the anthropogenic actions that change the forest structure and speeds up processes of soil erosion. According to the PRODES project, up to 2017 the accumulated deforestation in Paragominas reached ca. 45% (8,744 km^2) of its territory. These areas have been converted to other land uses and were intended for livestock raising and crop production, mostly grain cultivation, with practices characterized by monoculture, intense mechanization, and agrochemical inputs (Alves, *et al.*, 2014). After processing the satellite imagery, 9% (1,752 km^2) of the municipality was identified in the high vulnerability category presenting sparse vegetation or exposed soil (**Fig. 5 D**).

The most stable Paragominas areas correspond to about 76% (14,793 km^2) of the municipality, which is occupied by ombrophilous forest with altered primary and secondary vegetation under the advanced successional stage, thus, low potential for vulnerability to soil erosion. In this advanced stage of succession, there is a greater production of litter (Pezzatto & Wisniewski, 2006; Barbosa & Faria, 2006) that may favor soil protection, since it is the main form of nutrient return to the soil and moisture retention (Espig *et al.*, 2009).

3.3.1.5. Climate attribute

The potential capacity of rainfall to accelerate the process of soil erosion is related to the precipitation intensity in a region (Bertoni & Neto, 2008; Guerra, Silva & Botelho, 2009). The climate in humid equatorial Amazon is very favorable to the vegetal production benefiting the forest protection, acting as a huge thermostat avoiding extremes of temperature (Schmidt, 1947), and through rainfall and temperature, the climate controls the weathering of a region (Mota *et al.*, 2009). The erosion process caused by rainfall (Santos *et al.*, 2010) is the result of soil particles surface disaggregation, due to the energy of the drop's impact and by the surface runoff force. The detachment and transport of sediments promote soil losses by floods (Bertol *et al.*, 2007; Bertoni & Neto, 2012).

Rainfall directly influences erosion processes, and in Paragominas the pluviometric intensity average (mm/moth) is smaller than 1 mm during the dry season (June to November) and more than 1,000 mm in the rainy season (December to May). As a consequence, the entire municipality has value 2 - 2.4 moderate (52%; 10,044 km^2), to hight-moderate 2.5 – 2.7 value (39%; 7,591 km^2) vulnerability to soil erosion for the climate attribute (**Fig. 5 E**).

Only 1.5% (311 km^2) of the municipality has a value of 1.7-1.9 vulnerability considered medium-low and another 8% (1,557 km^2) considered to be a high vulnerability potential to soil erosion (2.8 - 3 vulnerability value). As the dry and rainy periods in the municipality are well defined, they do not cause a significant impact on soils covered by vegetation. The rainfall of a given region is considered a risk factor due to the production of sediments per unit of drainage area which raises with the increase of the drainage area, the larger the river basins, the greater the possibility of possible erosions (Oakes *et al.*, 2012).

3.3.2. Estimation of soil loss according to (RUSLE).

3.3.2.1. Factor R (Erosivity of rains)

Soil erosivity of this factor involves the disintegration of soil particles, transported and deposited by rainfall and surface runoff of water on the soil (Crepani, 2004). The values of this factor for the 28 rainfall stations vary from 5,621 to 17,540 MJ.mm/ha.h, with an average of 13,500 MJ.mm/ha.h, standard deviation of 1,630 MJ.mm/ha.h. Paragominas has a very heterogeneous R-factor, however, the highest and lowest values of erosivity estimation indices are found in the southeast of the municipality, which are well-vegetated zones (**Fig. 6 A**). According to da Silva (2004), the highest values for the R-factor were found in the Amazon region, in that study the strong class of erosivity is between 7,000 to 9,800 MJ.mm/ha.h, and very strong are higher than 9800. In Paragominas only 1.7 % (325 km^2) in the strong category and 97.1% (18,892 km^2) in a very strong class.

3.3.2.2. Factor K (Soil erodibility)

This factor is related to the soil and understanding its characteristics and properties is primordial since its composition can affect the velocity of infiltration, water storage capacity, permeability, transport by rain, runoff, splash, dispersion, and abrasion (de Lima, 2003). The soils most likely to undergo laminar erosion are in a small part of the northeast of the municipality and in the administrative limits (rivers boundaries) present in the soils argisols (2%, 389 km^2) and gleysol (2%, 389 km^2) a small part of the municipality, most of the municipality is latosol type (79%, 15,377 km^2) and has a low factor K (**Fig. 6 B**).

3.3.2.3. Factor LS (Topographic factor)

Considered as one of the factors of high relevance, the factor has a strong influence (Wischmeier & Smith, 1978), because the volume of the floods is directly related to the degree of slope of the terrain; however, in the municipality of Paragominas there is not a high degree of slope. **Fig. 6 C** shows the distribution of the factor LS, the lowest LS value was between 0 - 0.029 t h Mh^{-1} mm^{-1} corresponding to 8% (1,677 km^2) of the municipality, while the higher value that was above 9 t h $Mh^{-1}mm^{-1}$, represents only 0.03% (7 km^2) of Paragominas. The majority of Paragominas (80%, 15,539 km^2) is between 0 to 1 t h $Mh^{-1}mm^{-1}$, with an average of 0.2 t h $Mh^{-1}mm^{-1}$ and a standard deviation of 0.9 t h $Mh^{-1}mm^{-1}$.

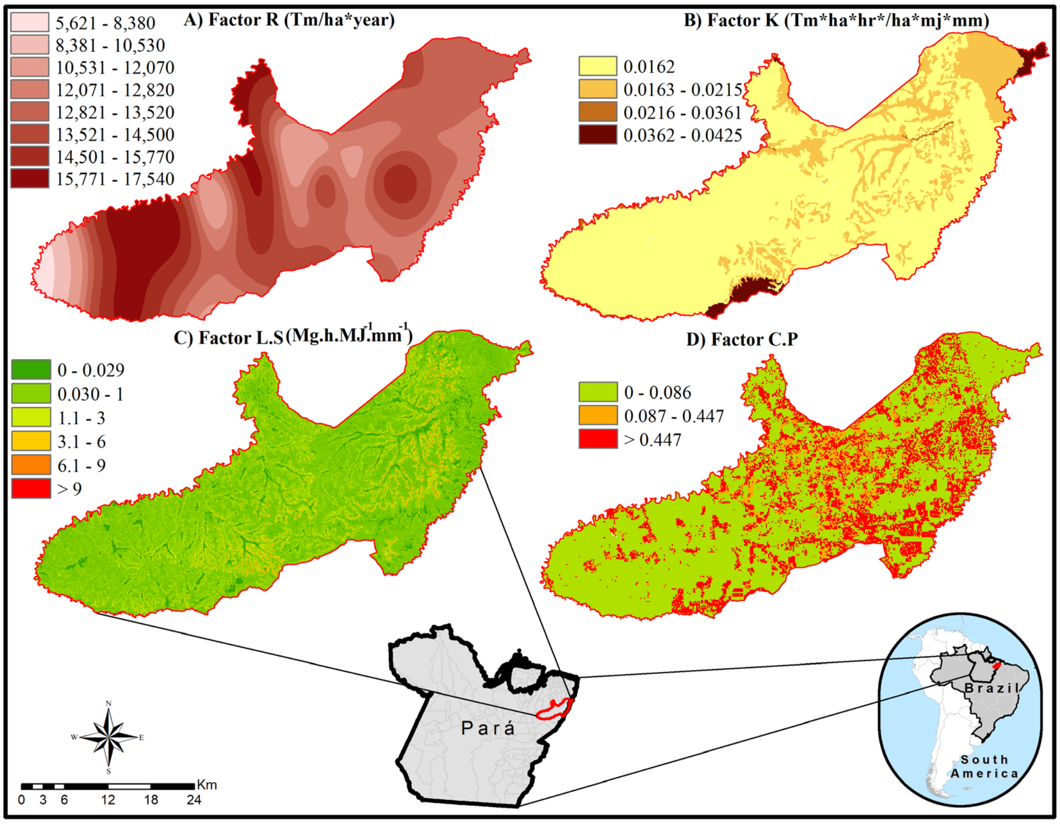


Fig. 6. Erosion estimation calculated by the RUSLE method, based on A) Factor R; B) Factor K; C) Factor L.S, and D) Factor C.P (*Elaborated by the authors*).

3.3.2.4. Factor C (use/soil management) and P (conservationist practices)

Brazil loses per year tons of soil from the surface layers, which are dragged into the streams, rivers, lakes, and lowlands, resulting in an increase in bed volume and a decrease in the soil covered by vegetation (Dlamini *et al.*, 2011; Podwojewski *et al.*, 2011). When spatializing the factor CP values with soil types, it was observed that the lowest values are found in the latosols, dystrophic argilubic pintossol, and gleysol soils, while the petroferric eutrophic have a higher C.P value. Values range from 0 to 1, with an average of 0.12 and a deviation of 0.21. Paragominas has an area of 71% (13,749 km^2) with a CP factor between 0 - 0.086, where the primary and secondary vegetation is located, between 0.087 - 0.047 only 6% (1,076 km^2) is found in cattle ranching regions and in 24% (4,640 km^2) of Paragominas found a C.P factor greater than 0.048 zones under agricultural cultivation (**Fig. 6 D**).

In the classification of land use and cover, the expressive classes were primary vegetation 47% (9,228 km^2), secondary vegetation 22,9% (4,463 km^2) and pasture 21,8% (4,252 km^2) respectively, however the latter (pasture) has a higher CP value, followed by deforestation (1.7%, 337 km^2) and agriculture (5.6% 1.086 km^2). The data of intense agricultural production (Schlesinger, 2010) indicates that areas under crop production are increasingly overused around the world, exhausting soil capacity and making them less resilient and more vulnerable to erosion (Mazzali, 2000).

3.3.3. Soil loss estimation and vulnerability (Ecodynamic concept and RUSLE method)

These methods are widely applied in Brazil, allowing quantification and regionalization of the area with the highest risk of soil erosion. Paragominas presents ca. 77% (15,064 km^2) of its territory with low-moderate (t ha-1 year-1) degree of soil loss calculated by the RUSLE method, not so different from the method based on the ecodynamic concept, which was 60% (11,485 km^2) with a low and low-moderate degree of erosion of vulnerability to soil erosion (1 - 1.8 value). A similar situation was found for areas with high soil loss, with high soil loss, which represented only 3% (642 km^2) degree of erosion according to RUSLE and 2.7% (584 km^2) according to the ecodynamic concept, (**Table 10; Fig. 7**). This erosion can cause the flow of superficial layers carrying organic matter, nutrients, and seeds, resulting in high production costs (Parker *et al.*, 1995).

In almost all variables analyzed in the two methods concerning their potential of soil erosivity, the values are similar. Soil and slope attributes, for example, obtained 79% (15,377 km^2) and 80% (15,572 km^2) respectively of the municipality with low vulnerability value and erosivity estimation. A similar situation was noted for the low vulnerability degree for the vegetation attribute (soil use and cover), the result of erosivity value was 76% (14,793 km^2) for the ecodynamic concept and 71% (13,820 km^2) for calculation of RUSLE (C.P). The only exception was with the climate and factor R attribute, in both methods the rainfall data are used to generate the index vulnerability and erosion estimation, only 1.5% (292 km^2) and 1.3 (253 km^2) of Paragominas are considered as low vulnerability grade, according to the ecodynamic concept and RUSLE respectively. Consequently, for this factor, vulnerability values and erosion estimation were more significant throughout the municipality.

Table 9. Estimates of loss and vulnerability to soil erosion in Paragominas.

RUSLE method				Ecodynamic model method			
Loss of soil (t ha^{-1} year^{-1})	Degree of erosion	Municipal area		vulnerability values	Degree of erosion	Municipal area	
		Km²	%			Km²	%
0-10	Low-moderate	15,064	77.4	1-1,5	Low	4,672	24.3
10.1-50	Moderate	2,093	10.8	1,6-1,8	Low-moderate	6,813	35.4
50.1-150	High-moderate	1,665	8.6	1,9-2,1	Moderate	5,256	26.9
151.1-200	Hight	218	1.1	2,2-2,4	High-moderate	2,141	10.7
>200	Very high	424	2.2	2,5-3	Hight	584	2.7
-	-	19,465	100	-	-	19,465	100

Source: Elaborated by the authors.

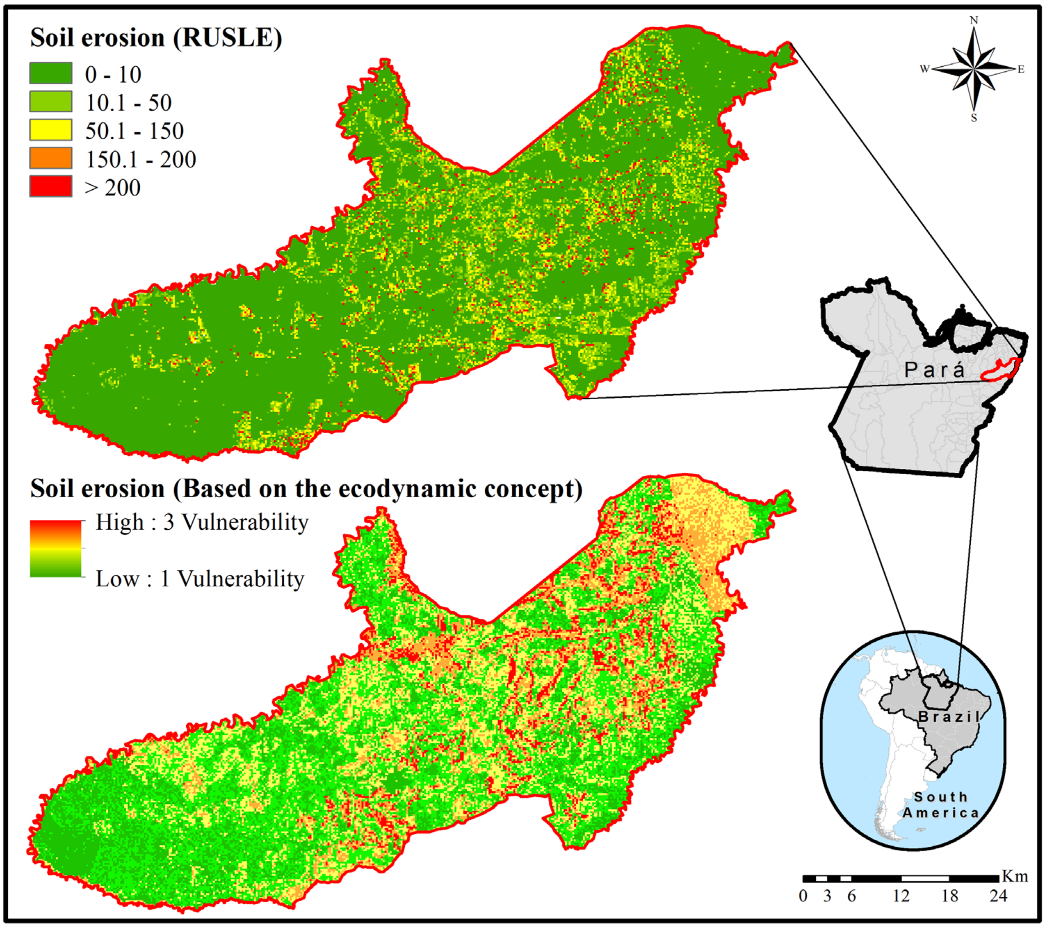


Fig. 7. Soil erosion soil calculated by the method based on the **RUSLE** and **ecodynamic concept** (*Elaborated by the authors*).

3.3.4. Management and Soil conservation

The conservation practices aim to control soil and water losses in areas with agricultural activities, for example, without altering the productive capacity of the soil. Thus, it is important to adapt the soil conservation to the occupation of the area according to its capacity of use, so that the management practices can favor the erosion control, improving the water infiltration capacity in the soil, reducing the surface runoff that leads to the formation of aggregates and minimizing the impact of raindrops.

The conservation processes can be mechanical, edaphic, and vegetative, depending on the cropping system. However, for a good result, it is necessary to apply them simultaneously, since each one develops a function and solves a part of the problem. The mechanical practices use artificial structures for the conduction or interception of surface runoff, while edaphic practices are related to the cropping system, controlling erosion and contributing to better soil fertility. On the other hand, the vegetative activities combat erosion based on the protection of the soil against the action of precipitation using the vegetation. For this reason, the maintenance of adequate vegetation coverage in the soil is one of the basic principles for conservation, a process that is hampered by deforestation.

Paragominas was born in the troubled development process of the Brazilian Amazon, which was encouraged by the government to develop the region economically (Mahar, 1979). With around 50 years it owns already ca. 45% (8,773.3 km^2) from its territory deforested and converted into other uses (INPE, 2018). Over the years these deforested areas have been converted into other uses and the municipality is currently characterized mainly by agriculture, logging, and mining extraction (especially bauxite).

In the classification analyzed in this study for the period from 2004 to 2017, we noticed that between 65% and 70% of Paragominas is covered by primary vegetation altered and secondary vegetation. In the last year (2017), for example, about 47% (9,110 km^2) of the Paragominas territory was covered by altered primary vegetation, 23% (4,406 km^2) by secondary vegetation, and 5.5% (1,074 km^2) correspond to agricultural activity (**Table 10**).

The values in the mapped area were not so different from the agricultural areas available in the SIDRA system. However, when we analyzed the standardized agricultural production data of the planted area, harvested tone, and revenue, we noticed that in 2008 there was an increase in the cultivated area and the quantity of harvested product, despite the decrease in revenue. The Worst scenario was identified in the year 2010 when crop area and revenue decreased while acreage

Table 10. Land use classification (Terraclass of 2004 to 2014 and sentinel-2 of 2017)

Class	TerraClass (km²)					Unsupervisionad Classification (km²)
	2004	**2008**	**2010**	**2012**	**2014**	**2017**
Annual Agriculture	172	449	683	835	1,019	1,074
Unobserved area	1275	2,378	264	1,702	859	-
Urban area	15	23	29	31	38	39
Deforestation	1,029	55	64	16	10	333
Forest	11,180	10,757	10,645	10,602	10,490	9,110
Hydrography	26	50	50	50	26	45
Minning	-	7	18	31	-	69
Occupation mosaic	27	23	12	7	44	24
Non-Forest	7	7	7	7	7	-
Others	16	5	34	8	4	166
Pasture with exposed soil	-	-	0	0	-	-
Clean pasture	2,871	2,775	2,678	2,569	3,148	-
Dirty pasture	540	712	418	334	441	4,199
Reforestation	-	-	134	252	208	-
Regeneration with pasture	707	224	1,005	281	405	-
Secondary vegetation	1,601	2,002	3,423	2,741	2,767	4,406
Total	19,465	19,465	19,465	19,465	19,465	19,465

Source: Elaborated by the authors.

increased. In 2012, it was the year of the best agricultural performance, according to SIDRA data, since there was a small increase in the area produced, with an increase in the area collected and a better performance of the income, during the same period the production of the head of cattle was one of the worst. Another atypical event was in 2014, in that year, production and harvest decreased, but revenue grew (**Fig. 8**). The trend of inverse proportionality between agricultural and livestock production was also noticed, that is, when there is a decrease in livestock production, agricultural production rises, evidenced from 2008.

Paragominas was one of the Amazon municipalities with a higher rate of illegal logging for many years. According to Imazon (Institute of Man and the Environment of the Amazon), during the period from 2007 to 2012, ca. 74% (960 km²) of the municipality's logging was carried out without authorization, in all that years of monitoring the logging without permission was higher than the authorized one (**Fig. 9**).

When analyzing the official data of wood production in m^3 and revenue of SIDRA/PEVS - Production of Plant Extraction and Silviculture, we noticed that there is a significant difference between the production of wood in m^3 with the generated revenue. In the period from 2008 to 2012 the revenue increased, while the harvest decreased, that difference is quite evident when comparing the area of logging monitored by Imazon with the data of harvest and revenue in 2008, that year the logging in the municipality was 80% (601 km^2) of the total (749 km^2), and the data of the PEVS also show an overestimation of the revenue concerning production (**Fig. 10**), this can be explained by the illegality in the sector.

Another quite significant activity mapped out in this study was mining. This activity has existed for a long time, but in the past, it did not require sophisticated technological processes. Before the areas were mined with a semi-mechanized

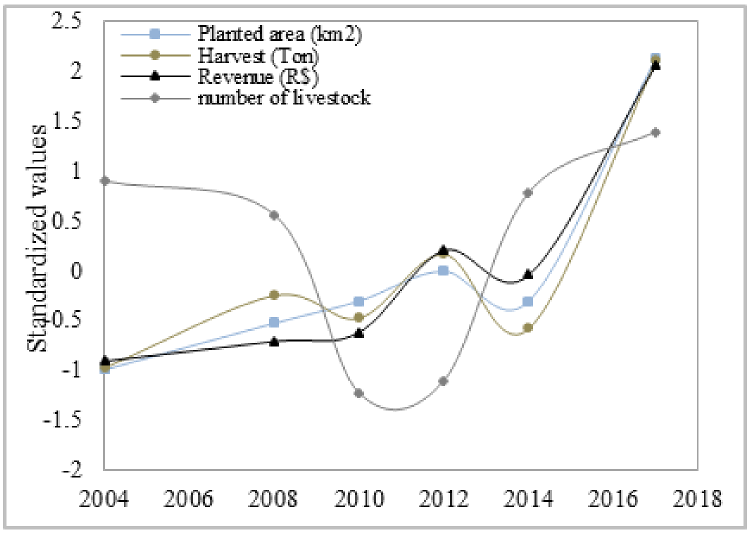


Fig. 8. Panted area, harvest, and revenue of the agriculture data and number of livestock (*source: authors*)

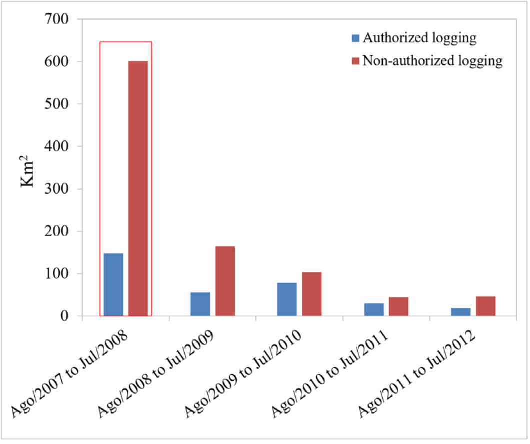


Fig. 9. Logging monitoring (Imazon)

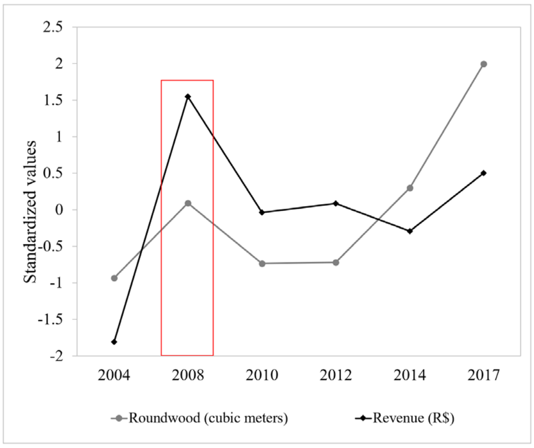


Fig. 10. Logging data (PEVS)

extraction system, today they present a complex set of large equipment. One of the ores with a lot of potential in the Amazon is bauxite, which produces aluminum, which is used in various segments, such as packaging, transportation, civil construction, electricity, consumer goods, machinery and equipment, and others. It is important to point out that mining activity significantly improves the economy of a region, but also causes great degradation since it unbalances the environment in the huge extension of land and changes the soil components (Reis, 1999).

Paragominas has one of the greater enterprises of mineral activity of the state. According to DNPM (2018), the municipality presents 43% (8,308 km^2) of its territory undermining process, with the large majority 39% (3,246 km^2) having a research permit, 27% (2,318 km^2) with a request of mining and 25% (2,070 km^2) in concession (**Fig. 11 A**). Regarding the ore class, bauxite represents ca. 72% (5,998 km^2) of the total in mining processes classified by DNPM (**Fig. 11 B**). As for the use of the extracted minerals 53% (4,425 km^2), there is no information about the use, for the metallurgy activities are destined 25% (2,035 km^2) and about 1,726 km^2 (21%) of the area is destined for extraction of the ore for industry (**Fig. 11 C**).

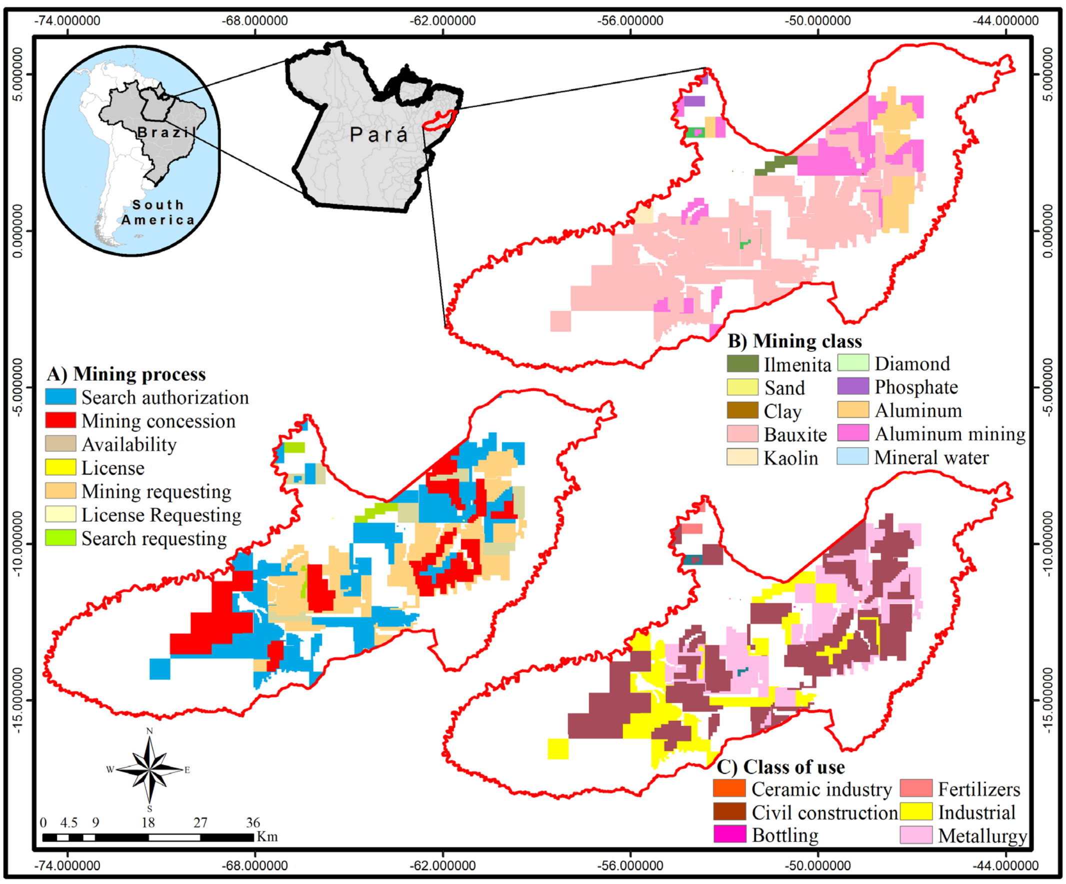


Fig. 11. DNPM mining data (*Elaborated by the authors*).

3.4. CONCLUSIONS

The attributes analyzed in the two methods presented in their majority low and intermediate vulnerability estimation and potential of soils loss, it requires attention to avoid such regions to become areas with high potential for erosion vulnerability in the future. For the two analyzed methods (Ecodynamic concept and RUSLE) only 3% of Paragominas had a high potential of erosivity. The identification of regions with vulnerability to soil erosion potential is efficient to assist decision making and territorial management, to answer important environmental questions, determine low operating costs, plan activities in management practices, and environmental conservation of the municipality.

Monitoring erosion over large area extensions is a costly process, so geoprocessing becomes a useful tool for estimating soil loss. The multicriteria analysis using GIS tools (Geographic Information System) was extremely important in this study because they mapped and estimated the vulnerability potential to soil erosion for the Paragominas municipality; however there are not many studies on the subject in the Amazon region, therefore it is necessary to further researches with field analysis in the region to corroborate the results.

Soil erosivity is a natural process, however, inadequate human actions regarding soil use generate irreversible environmental degradation. The intense erosion process, for example, leads to soil impoverishment and pollution of water networks, causing economic, social, and environmental problems on a scale from local to global. Thus, the results of this study reveal the need for greater attention in the areas of greater environmental risk.

Good data collection and analysis of rainfall, topographic information, land cover, and management system lead to significant results to be obtained from areas susceptible to degrading erosive processes. The studies associated with soil erosion are fundamental, both for agricultural conservation practices, to subsidize the environmental planning, in which economic practices must be calculated under conservationist principles.

3.5 ACKNOWLEDGEMENTS

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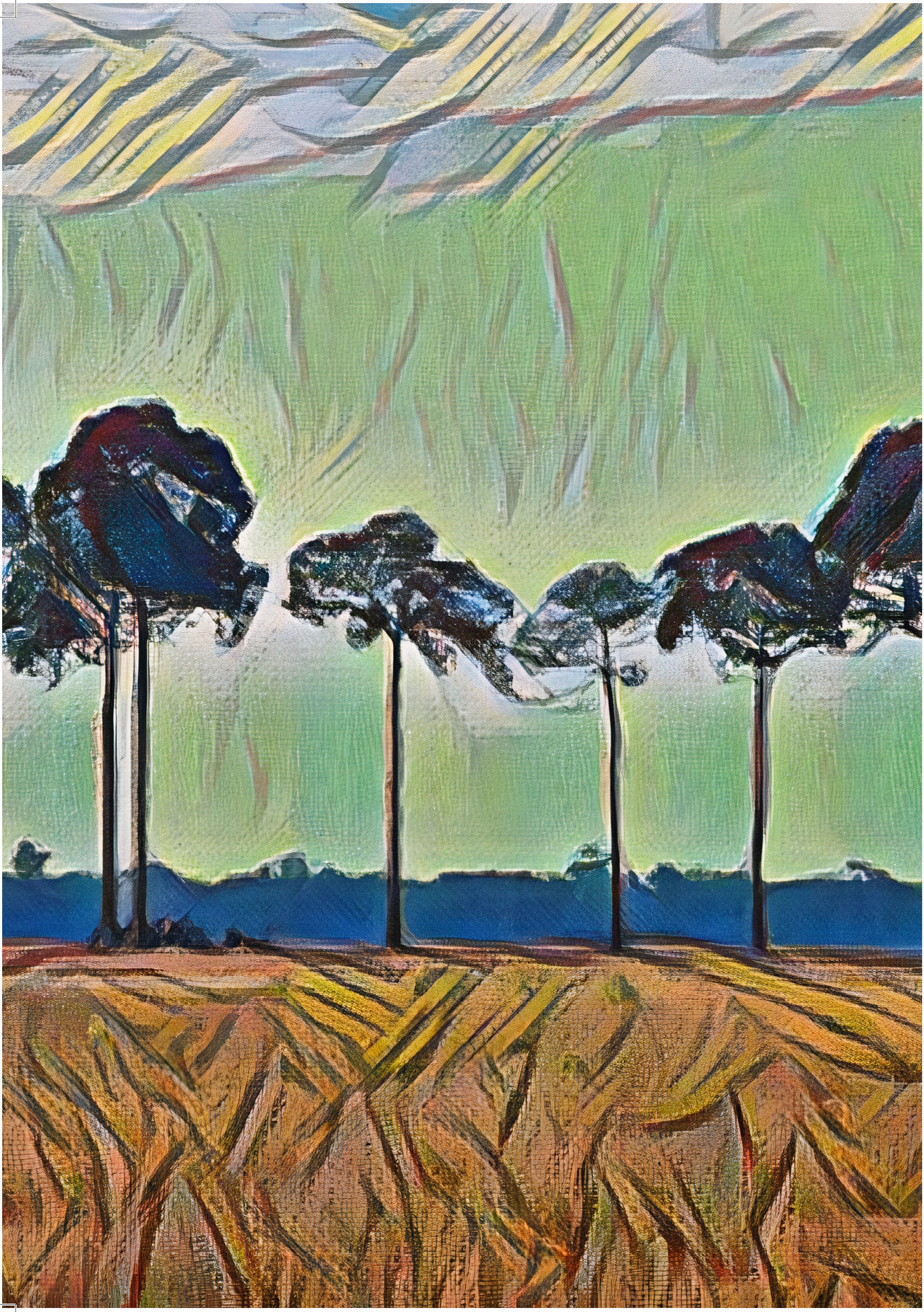

4. FOREST RESTORATION EVALUATION THROUGH INDICATORS IN AREAS OF BAUXITE MINING

CHAPTER IV

Forest Restoration Evaluation Through Indicators in Areas of Bauxite Mining*

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ABSTRACT

The state of Pará ranks second in Brazilian mineral production, where bauxite accounts for 84% of total mineral extraction, with negative impacts on the environment as a result. The determination of objectives and targets using environmental indicators as a tool to evaluate forest restoration processes is essential in the recovery of these exploited areas. This study aimed at evaluating the efficiency of forest restoration techniques by means of 13 qualitative and quantitative indicators for monitoring post-bauxite mining operations. Permanent plots were implanted in revegetated areas with the use of two techniques: planting of seedlings and stewarding of natural regeneration. It is concluded that the techniques are efficient for the recovery of forested area. However, natural regeneration showed greater efficiency for restoration for Density, Erosion and Exotic Species indicators. Still, natural regeneration should not be the sole option in the processes of ecosystem restoration, since planting proved to be more efficient for some indicators.

Keywords: mining, forest succession, topsoil.

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4.1. INTRODUCTION

Environmental degradation results in negative impacts such as loss of biodiversity, changes in the hydrological cycle, emission of deforestation gases, and especially loss of opportunity for sustainable economic use of the forest, such as the extraction of non-timber forest products (Fearnside, 2006).

Currently, mining is one of the main sources of raw material for industrial processes (IBRAM, 2015). In the municipality of Paragominas, in the state of Pará, bauxite-mining operations began in the 2000s, on the Milônia III plateau, with an initial production estimated at 4.4 million tons p.a. (Brandt, 2003). A licensed mining company has to comply with Brazilian legislation, which includes the miners' responsibility for the environmental recovery of impacted areas (Brasil, 1940, Art. 7, § 2). Thus, a mining entrepreneur must propose a Recovery Plan for Degraded Areas (PRAD) to be approved by the official body licensing his enterprise.

Thus, the recovery of the degraded areas is to follow the mining operations, including the revegetation of the mined plots. The monitoring and verification of the success of the recovery and of the coherence of the actions in the field with what has been established in the Recovery Plan for Degraded Areas follow this. The said Plan should consider the technical solution that is adequate to the specific general circumstances of the site, and should have clear goals and objectives that are linked with the actions on the field, in order to favor the restoration of soil conditions that have been degraded by the mining activity, to provide future use of the resources thereof (IBRAM, 1992).

Concerning this, monitoring methodologies are to be established to search for criteria and indicators that can evaluate the quality of the ecosystem recovery in various Brazilian biomes, and should be not only easily measurable, but sensitive to system stress, predictable, integrative and reliable (Durigan, 2011), taking into account the degradation factor, the specific conditions of each locality, area history, and vegetation dynamics (Andrade et al., 2014).

Therefore, this study aims to evaluate the efficiency of forest restoration techniques (the planting of seedlings and stewarding natural regeneration) by means of monitoring indicators in the bauxite-mining area of Paragominas, in the southeast of Pará state.

4.2. MATERIAL AND METHODS

4.2.1. Characterization of the study area

The research was developed in the municipality of Paragominas, Pará state, in Mineração Paragominas Ltd., (**Figure 1**), specifically on the Miltônia III plateau, (03°12' and 03°20' S and 47°40' and 47°46' W) (Brandt, 2003).

4.2.2. Sampling units

In order to evaluate the indicators, the monitoring data of the area as established in 2009 (terrain reconfiguration and soil deposition) were analyzed. The area is composed of 71.44 ha where the seedling planting technique was used in six permanent plots (PP), and 21.04 ha where the technique of natural regeneration (NR) was used on three plots installed, totaling 92.48 monitored hectares. Data from five monitoring campaigns were used (2013 and 2014 – May and November –, and 2015 – only in May).

In the planting areas, the plots are 20 × 50 m (1000 m^2) and were evaluated at two sampling levels: Level I (20 × 50 m), where all planted individuals were evaluated, and Level II (10 × 10 m), in which all plants with a stem diameter ≥

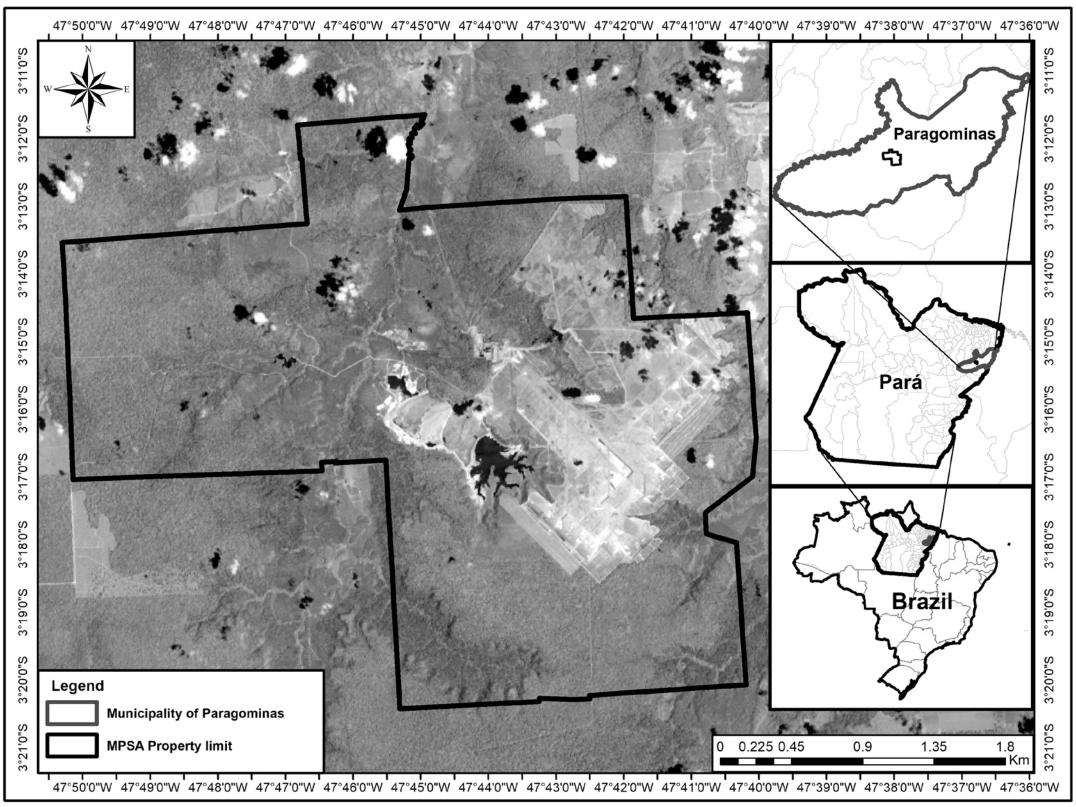

Figure 1. Location of the enterprise where the study was held – Paragominas, Pará state.

1 cm were also evaluated. In the natural regeneration areas, the implanted plots are 10 × 25 m (250 m^2), where at Level I all individuals were evaluated at DBH ≥ 10 cm, and at Level II subplots of 5 × 10 m all individuals with DBH < 10 cm were evaluated.

For the evaluation of the forest litter indicator, the permanent plots installed in the two techniques (planting and natural regeneration), plus other three Evaluation Units in the forest fragment area that did not undergo a direct impact by mining were analyzed, in order to obtain a reference of the quantitative factor of litter to establish a comparison between the techniques.

4.2.3. Choice of recovery assessment indicators

For the selection of indicators the rapid assessment methodologies were used, as cited by Brancalion et al. (2012), and the *Pacto pela Restauração da Mata Atlântica* – Pact for the Restoration of the Atlantic Forest – (Rodrigues et al., 2009) and studies by Salomão et al. (2002) in heterogeneous reforestation in the Saracá Taquera National Forest plateau.

The following principles of evaluation in the context of forest restoration in Paragominas were selected: Principle I – evaluation of the structural recovery of the canopy to acknowledge the ecological processes of occupation of the understory in the area through the composition of the species either planted or coming from natural regeneration –; and Principle II – monitoring of the ecological trajectory, whose objective is to monitor whether the regeneration dynamics in the area is leading to the restoration within the desired and expected trajectory (Table 1).

4.2.4. Collection of information

The campaigns took place in the months of May and November, with the months from December to May being the most rainy period and from June to November the driest (Andrade, 2011), with dendrometric data collection (total height and circumference) and crown area projection (collection of longitudinal and transverse measurements to calculate the ellipse area), botanical samples were obtained for the floristic data of the registered species. For the quantification of the forest litter stock, a template with width, length and height dimensions of 20 × 20 × 7 cm was used, with the collection place within the vegetation monitoring plots (six random collections).

Qualitative data were obtained in an immeasurable manner, based on the observation of the presence or absence of a certain aspect or phenomenon.

The registered species were herborized and their scientific determination made

Table 1. Criteria and Indicators used in the evaluation of techniques: planting of seedlings and stewarding natural regeneration in post-bauxite mining areas in Paragominas, Pará state, adapted from Brancalion et al. (2015) and Rodrigues et al. (2009).

EVALUATION INDICATORS	DESCRIPTION
STRUCTURE	Assess the formation of forest cover in the area
Recovery of Structure and composition of vegetation	Evaluate the resilience power of the area and the vertical and horizontal distribution.
Degree of cover/shading	Evaluate the percentage of soil cover from the crown shade.
Presence of natural regeneration	Evaluate the response of the forest succession process from the seed bank contained in the soil.
Presence of erosion	Evaluate the presence of laminar erosion, aiming to assess the degree of soil conservation.
Forest leaf litter	To evaluate the accumulation of organic matter in the soil, important to determine the viability of plantations that aim at restoring.
Density of plants	Evaluate the amount of individuals of shrub and tree species.
Diversity	Evaluate the proportion of individuals' distribution between species, calculated by the Shannon diversity index (H').
Average plant height	Evaluate if the height of the plants is consistent with the age of the individuals.
Basal area	Assess the degree of cover of individuals, or space required by them.
MONITORING ECOLOGICAL TRAJECTORY	Monitor the ecological trajectory leading to restoring.
Maintenance of the Area under Recovery	To evaluate the dynamics of vegetation growth and mortality and the return of ecological processes.
Mortality	Evaluate the species that are most adapted to the environmental conditions of the area in the process of restoring.
Increase in Diameter	Quantify the rate of growth of plants.
Presence of non-invasive alien species	Evaluate the incidence of regional and exotic species and morphospecies to acknowledge the potential for biological invasion.
Presence of endangered species	Evaluate the species in the threat of extinction level.
Presence of traces of fauna return	Evaluate the return of wild fauna in the area under restoration, identifying traces of animals that act as agents in plant reproduction.

in the IAN Herbarium of the Eastern Amazonia Embrapa and then sent to the Felisberto Camargo herbarium of the Federal Rural University of Amazonia – UFRA –, since these were mostly non-fertile specimens.

4.2.5. Phytosociological analysis

For the analysis of the horizontal structure, calculations included the parameters of Relative Density (RDe in%), Relative Frequency (Rf in%), Relative Dominance (RDo in%) and Family Importance Value Index (FIV) in%), which showed information on spatial distribution and the importance of plant communities for the ecosystem (Ellenberg & Mueller-Dombois, 1974). Floristic diversity was also assessed using the Shannon Diversity Index (H') on the natural logarithmic basis (Shannon & Weaver, 1949).

The Shannon-Weaver Index (H') measures the degree of uncertainty associated with the identity of the species in a sample. Thus, the greater the value of H', the greater the uncertainty, which can be understood as diversity, and attributes equal weight among rare and abundant species (Magurran, 1989).

4.2.6. Criteria for the evaluation of indicators

In the evaluation, different weights were attributed according to their importance, considering that the indicators of high importance (weight 3) help to understand when processes or phenomena present problems that can compromise the restoration in the short term, making the correction difficult (degree of tree cover/shading, presence of natural regeneration, presence of erosion, forest litter, plant density, diversity, mortality, increase in diameter and the presence of traces of fauna return). The indicators of medium importance (weight 2) indicate problems that can compromise the restoration in the medium term, being easily corrected (mean plant height, basal area and presence of non-invasive alien species). Finally, those of low importance (weight 1) do not compromise the planting, thus being positive indicators, and for this reason should be stimulated (presence of threatened species).

Table 2 shows the definition of the criteria intervals for each indicator as defined in the literature on ecological succession and restoration (Brancalion et al., 2015; Luizão et al., 2014; Salomão et al., 2012; Oliveira, 1998).

Each score was multiplied by the weight of the indicator according to its degree of importance, and it is possible to perform the algebraic sum to define the final score in recovery, which was compared to the hypothetical score obtained by an ideal project that reached a maximum score in all the indicators. Based on this result, the best technique was defined – the one closest to the maximum score for an ideal project (102 points).

Table 2. Evaluation criteria for the analyzed parameters based on the recommendations for restored areas with planting of seedlings and conduction of natural regeneration.

Indicator	Criterion	Score	Analysis	Reference
Degree of tree cover/ shading	< 20%	0	Individuals with DBH ≥ 5.0 cm	Brancalion et al. (2015)
	Between 20 and 50%	1		
	Between 50 and 80%	2		
	> 80%	3		
Presence of natural regeneration	Presence	3	Qualitative	
	Absence	0		
Presence of erosion	Presence	0	Qualitative	
	Absence	3		
Forest leaf litter	< 4.1 t ha^{-1}	0	Collection and weighing of litter	Luizão et al. (2014)
	Between 4.1 and 7.7 t ha^{-1}	1		
	Between 7.7 and 9.4 t ha^{-1}	2		
	> 9.4 t ha^{-1}	3		
Density of plants	< 1500 ind.ha^{-1}	0	Individuals with Height ≥ 50.0 cm	Brancalion et al. (2015)
	Between 1500 and 2000 ind.ha^{-1}	1		
	Between 2001 and 3000 ind.ha^{-1}	2		
	> 3000 ind.ha^{-1}	3		
Diversity	< 1.0 nats ind^{-1}	0	All sampled individuals	Brancalion et al. (2015)
	Between 1.1 and 2.0 nats ind^{-1}	1		
	Between 2.1 and 3.0 nats ind^{-1}	2		
	> 3.0 nats ind^{-1}	3		
Average height	< 6.0 m	0	Individuals with DBH ≥ 5.0 cm	Salomão et al. (2012)
	Between 6.0 and 7.0 m	1		
	Between 7 and 9 m	2		
	> 9 m	3		
Basal area	< 7.0 m^2 ha^{-1}	0	Individuals with DBH≥ 5.0cm	Salomão et al. (2012)
	Between 7.0 and 12.0 m^2 ha^{-1}	1		
	Between 13.0 & 19.0 m^2 ha^{-1}	2		
	> 19.0 m^2 ha^{-1}	3		
Mortality	> 10%	0	Individuals with DBH ≥ 5.0 cm	Brancalion et al. (2015)
	Between 5.1 and 10%	1		
	Between 3.1 and 5%	2		
	Between < 3%	3		
Increase in Diameter	< 0.3 cm year^{-1}	0	All individuals with 5 measurements	Salomão et al. (2014); Oliveira (1998)
	Between 0.3 and 0.5 cm year^{-1}	1		
	Between 0.6 and 0.7 cm year^{-1}	2		
	> 0.7 cm year^{-1}	3		
Presence of non-invasive alien species	Presence	0	Qualitative	Brancalion et al. (2015)
	Absence	3		
Presence of endangered species	Presence	3	Qualitative	Brancalion et al. (2015)
	Absence	0		
Presence of traces of fauna return	Presence	3	Qualitative	
	Absence	0		

Source: Adapted from Brancalion et al. (2012).

4.3 RESULTS AND DISCUSSIONS

4.3.1. Floristics and phytosociology

Of the 542 individuals (from seedlings) monitored in May 2015, 371 individuals (1,293.3 ind.ha^{-1}) in the planting of seedlings belong to 106 species (67 genera and 24 botanical families), while in natural regeneration 171 individuals (8,733.3 ind.ha^{-1}) are distributed in 27 species (22 genera and 16 botanical families).

In the areas of planting of seedlings, the Family Importance Value Index – FIV – showed Solanaceae with 23.2%, Malvaceae with 26.5% and the most expressive was Fabaceae, with 135.6%. For Fabaceae, higher numbers of species are recorded in the Brazilian flora (Forzza et al., 2010). This family is important in ecological restoration strategies because of its association with nitrogen-fixing bacteria (Sprent, 2001).

In the areas under natural regeneration there was a better balance between the values found for FIV. The three families that stood out were Urticaceae with 38.8%, Fabaceae with 40%, and Hypericaceae with 46.9% of FIV (13 families found in the survey). Although Hypericaceae did not show the largest number of species (1 species), it obtained the largest number of individuals (1907 ind.ha^{-1}) and basal area (3.61 m^{2} ha^{-1}).

In the planting of seedlings and in natural regeneration, the 12 families with the highest importance value index totaled 274.02% and 242.0%, respectively, of a maximum total of 300% of FIV, ratifying the ecological importance of these to the fauna and flora balance of the ecosystem that undergoes a process of restoration.

4.3.2. Restoration of vegetation structure and composition

4.3.2.1. Diversity of species

The value of the Shannon index for the planting area recorded a mean value of 3.3 ± 0.2 for all sample units, while in natural regeneration the mean value was 2.2 ± 0.3. This result was already expected due to the number of species used in planting (147 species), while in natural regeneration there is a dependence on the germination of the seed bank contained in the soil and the dispersion of seeds from surrounding areas.

The result obtained for the H' index was below that recorded by Francez et al. (2007), which was 4.25 for managed forests in the municipality of Paragominas, and by Knight (1975), who found the range of the H' index for the Amazon rainforest between 3.83 and 5.85, which characterize high diversity forests.

According to Rodrigues & Gandolfi (2000), the recolonization of altered areas may have different floristic diversity and composition from the original one, which may affect the characteristics of the forest structure, depending on the degree of intervention. Comparison of the means through the t test at 95% probability showed that there was a significant difference ($p < 0.05$) between the evaluated methods.

4.3.2.2. Density of plants

The mean confidence interval for density in the area planted to seedlings was 975 ind.ha^{-1} ± 447.6, lower than that found in natural regeneration, which was 8,400 ind.ha^{-1} ± 2,540.2. The comparison of the means by the t test ($\alpha = 0.05$) indicated a significant difference between the evaluated methods ($p < 0.05$). This result can be explained by silvicultural treatments in the area of planting, such as: hoeing, crowning, ant control, influencing the development of regenerant individuals.

The emergence of species in a given area after its abandonment depends essentially on the available seed bank, which is influenced by the surrounding area conditions, taking into account the phenology of the species and the presence of dispersers transiting between these areas (Massoca et al., 2012).

4.3.2.3. Basal area

The mean value for the basal area in natural regeneration was 13.6 m^2 ha^{-1} ± 9.81, higher than that found for planting seedlings of 2.9 m^2 ha^{-1} ± 0.7. The comparison of the means through the t test ($\alpha = 0.05$) showed a significant difference between the evaluated methods ($p < 0.05$).

The basal area is used to verify disturbances or changes in the environment, since it evaluates the forest structure, which tends to reach stability more quickly when the measurements of species composition are compared (Letcher & Chazdon, 2009). In the secondary succession processes, high basal area values are expected in the intermediate phase due to the high density and increment in diameter (Chazdon, 2012).

4.3.2.4. Average height

The average height value obtained for the planting of seedling was 5.2 ± 0.5, while for natural regeneration it was 5.1 ± 0.42. The comparison of averages using t test ($\alpha = 0.05$) showed there is no significant difference between the assessed methods ($p > 0.05$). In the planting of seedlings, 76.4% of sampled individuals are equal or below 5.0 m height and 83% of natural regeneration individuals are within the same height class.

4.3.2.5. Degree of cover

The degree of cover of the planting area recorded average values that were 49.5% ±_17.6, higher than the average crown cover found in natural regeneration, which was 23% ±_9.1. The comparison of averages using a t test (α = 0.05) showed there is no significant difference as to soil cover between the assessed methods ($p > 0.05$).

The crown cover in the forest is a determining factor of the microclimate, impacting the growth and permanence of plantlets; weed encroachment through the reduction of luminosity on the soil – a determining factor for the floristic composition, affecting oxidizing processes of organic matter and controlling erosive processes (Melo et al., 2007).

The method for crown projection measurement did not prove to be practical, and demanded too much time, in addition to its inaccuracy due to the shape variation of the crowns that do not form a perfect ellipse.

According to Carnevale & Montagnini (2002), the understory shading by the crown of planted trees reveals a positive correlation with both density and richness of natural regeneration. Accordingly, the results found for this indicator corroborate what was verified for the density indicator, inasmuch as it was expected to find a positive relation between the number of individuals and the degree of cover.

4.3.2.6. Forest leaf litter

The total stock of forest leaf litter on the soil at the seedling planting area was of 10.1 $Mg.ha^{-1}$ + 2.28, a value that is close to the one found on the natural regeneration area of 10.5 $Mg.ha^{-1}$ + 1.13, both values are inferior to the quantity found for the surrounding Dense Ombrophilous Forest, of 12.1 $Mg.ha^{-1}$ + 2.42. These values coincide with several studies performed in the Brazilian Amazon on secondary forests with ages from 5 to 22 years, which according to Luizão et al. (2014) vary between 4.47 and 9.40 Mg.ha–1. However, according to Luizão (2007), the forest leaf litter production may vary considerably in time, mainly depending on the abiotic variables.

The comparison of averages using t test (α = 0.05) showed there is no significant difference for the quantity of forest leaf litter present in the three assessed areas ($p > 0.05$). The similarity between the environments may be related to climate conditions since the areas are in close proximity with little meteorological variation (Dickow et al., 2012).

4.3.2.7. Qualitative analysis

In the planting of seedlings, soil erosion soil was present in one of the assessed plots (17%), whilst in natural regeneration no erosion was identified. One of the possible causes of erosion may be the terrain reconfiguration process, which is not carried out in level curves, driving more sediment to lower areas, in addition to manual weeding performed two years after implementation of planting, removing regenerant individuals.

Salomão et al. (2014) reported that high-density planting and induction of natural regeneration are the most recommended practices for recovering degraded fragments. Therefore, the spacing used in planting (3 × 3 m) may have impacted the erosion process, since it does not promote a swift coverage of the soil. In the natural regeneration areas, higher soil coverage is observed, thus avoiding the driving and leaching.

In the planting of seedlings, natural regeneration was identified but in one sample unit, totalizing 83% of plots with the presence of regenerant individuals.

The regenerant individuals' response is directly related to the germinating capacity of the seed bank. According to the operational initial procedure for mining operations, the topsoil that is removed from suppression areas must be directly transported to recovery areas, ensuring there is no deposit of soils impacting the seeds' germinating power. In the case of this study, reports from the company indicate that the deposited topsoil was stored for four months before being spread, which could have impacted the loss of the species' germinating capacity.

According to Salomão et al. (2013), the selection of species for planting implementation is important for the community structure (abundance, spatial distribution, biomass, scale or cover) since this selection impacts the occurrence of the other species and consequently, the successful recovery of areas that were degraded by open-air mining.

4.3.3. Maintenance of the area under recovery

4.3.3.1. Mortality

The average mortality rate in the planting of seedlings was of 10.3% ± 4.5 per year. The period of higher mortality rate was in May 2014, with 16.2%, and the lowest mortality rate was observed in May 2015, with 5.3%. A study held in the 1980's and 1990's by Salomão et al. (2002) recorded a mortality below 10% over a two-year period of heterogenic reforesting operations on the Saracá Taquera plateau between 1996 and 1998.

In the area were the natural regeneration stewarding technique was implemented, the average mortality rate was of 15.5% ± 7.9. The lowest mortality rate was observed in the monitoring performed in November 2013, with 7.0%, and the highest rate was identified during the monitoring of November 2014, with 25.2%. The comparison of averages using t test ($\alpha = 0.05$) showed there is no significant difference in mortality rates between the two assessed techniques ($p > 0.05$).

4.3.3.2. Annual periodic diameter increment

The annual periodic increment in diameter in the seedling planting area was 1.09 cm year^{-1} ± 0.28, while in the natural regeneration area the increment was 1.71 cm year^{-1} ± 0.48. The comparison of averages using t test ($\alpha = 0.05$) showed there is a significant difference between the assessed methods ($p < 0.05$).

A study carried out by Salomão et al. (2014) in a 13-year reforestation process analyzing 69 species has found an average increment value between 0.01 cm year^{-1} and 2.5 cm year^{-1}, a higher value than the one found in this study. Also in Saracá Taquera, Salomão et al. (2006) found an average annual increment value of 1.02 cm year^{-1}, varying between 0.26 cm year^{-1} and 3.24 cm year^{-1}.

4.3.3.3. Presence of exotic and threatened species

Of the 106 species recorded in the seedling planting area, only two species were considered as exotic: *Bauhinia macrophylla* and *Bauhinia purpurea* (JBRJ, 2015), because they are not featured in the Brazilian flora. In the natural regeneration areas, no exotic species were found.

Exotic species must be controlled in areas under restoration in order to allow and stimulate the development of the more desired native species (TNC, 2013). Native species, particularly those of interest for the restoration, must be favored with actions such as the application of agroforestry treatment (fertilization, ant control, etc.), which might improve their development and stabilizing in the process of populating.

Regarding threatened species, the Red List of Threatened Species created by the International Union for Conservation of Nature (IUCN, 2004), the Official List of Threatened Species from the Brazilian Flora published by Ministry of Environment in Ordinance no. 443/2014 (Brasil, 2014), and the List of Threatened Species in the State of Pará published in the appendix of COEMA Resolution no. 54/2007 (COEMA, 2007), were consulted. Fifteen threatened species were found in the planting areas (*Amburana cearensis*, *Aspidosperma álbum*, *Astronium graveolen*, *Bauhinia rufa*, *Cedrela fissilis*, *Enterolobium schomburgkii*, *Genipa americana*, *Hymenaea courbaril*, *Hymenaea parvifolia*, *Inga laurina*, *Lecythis lurida*, *Parkia ulei*, *Pterocarpus santalinoides*, *Swietenia macrophylla* and

Zollernia paraensis) and two species in the natural regeneration areas (*Hymenaea courbaril* and *Hymenaea parvifolia*). In the natural regeneration areas, such fact is highly positive considering that the seed bank and/or dispersion process are favoring the natural forthcoming of such species, which is important for their perpetuation.

4.3.3.4. Signs of wildlife recovery

For this indicator, traces of feces of *Tapirus terrestris* (South-American Tapir), listed as vulnerable in the IUCN list of threatened species, were found in planting areas, as well as *Mazama americana* (red brocket); while in the natural regeneration area, no traces were found in the samples units.

The wildlife indicator results are essential for the understanding of plant and animal interaction with the purpose of studying the genetic diversity within populations of tree species by means of the genic flow that takes place with pollination and seed dispersion, which are impacted by the process of fragmentation and then recovery of the areas (Machado et al., 2006).

4.3.5. Overall evaluation of both indicator-based techniques

The consolidation of scores obtained for each technique has showed that the stewarding of natural regeneration (72 points) presented a higher score in comparison with the planting of seedlings (54 points), of the total score that would be obtained for a perfect project (102 points) (Table 3). Despite the difference, both techniques show satisfactory results for the recovery of areas after bauxite mining, provided a few adjustments are made.

The results show that some items must get more attention so that the goal may be met within the planned period, demonstrating the importance of monitoring and the application of assessment methods in order to enable the timely identification and correction of problems to establish sustainable restored forests (Brancalion et al., 2012).

According to Sanchez (2010), the recovery of mined areas takes into account the regulation of physical aspects and the restoration of the biotic environment, of which he lists four environment scenarios to be considered: topographic, edaphic, hydric and vegetative practices.

Brancalion et al. (2015) stated that one of the main problems in the restoration process is the definition of clear goals in assessing and monitoring so as to obtain a set of results that can be successfully interpreted at different moments of the trajectory. Studies must work towards establishing reliable and adequate indicators for each local reality.

Table 3. Overall evaluation of the indicators analyzed in forest restoration area after bauxite mining in Paragominas-PA.

Code	Indicator	Weight – Degree of relevance	Indicator Maximum Score	Maximum Final Score	Planting of Seedlings		Natural Regeneration	
					Obtained Score	Final Score	Obtained Score	Final Score
A	**RECOVERY OF THE VEGETATION STRUCTURE AND COMPOSITION**							
A.1	Diversity	3	3	9	3	9	2	6
A.2	Plant Density	3	3	9	0	0	3	9
A.3	Basal Area	2	3	6	0	0	3	6
A.4	Average Height	2	3	6	0	0	0	0
A.5	Degree of Coverage	3	3	9	2	6	2	6
A.6	Forest Leaf Litter	3	3	9	3	9	3	9
A.7	Presence of erosion	3	3	9	0	0	3	9
A.8	Presence of natural regeneration	3	3	9	3	9	3	9
B	**MAINTENANCE OF THE RECOVERY AREA**							
B.1	Mortality	3	3	9	0	0	0	0
B.2	Diameter Increment	3	3	9	3	9	3	9
B.3	Presence of Exotic Species	2	3	6	0	0	3	6
B.4	Presence of Threatened Species	1	3	3	3	3	3	3
B.5	Signs of Wildlife Recovery	3	3	9	3	9	0	0
Final Score				**102**		**54**		**72**

4.4. CONCLUSIONS

The applied indicators showed that both techniques assessed were efficient in recovering bauxite mined areas, whereas natural regeneration in the overall evaluation showed a higher efficiency for density, did not present erosion or exotic species in its areas. However, it should not be the sole technique to be used in ecosystem restoration processes, since in some indicators the planting of seedlings was more efficient (diversity and signs of wildlife recovery).

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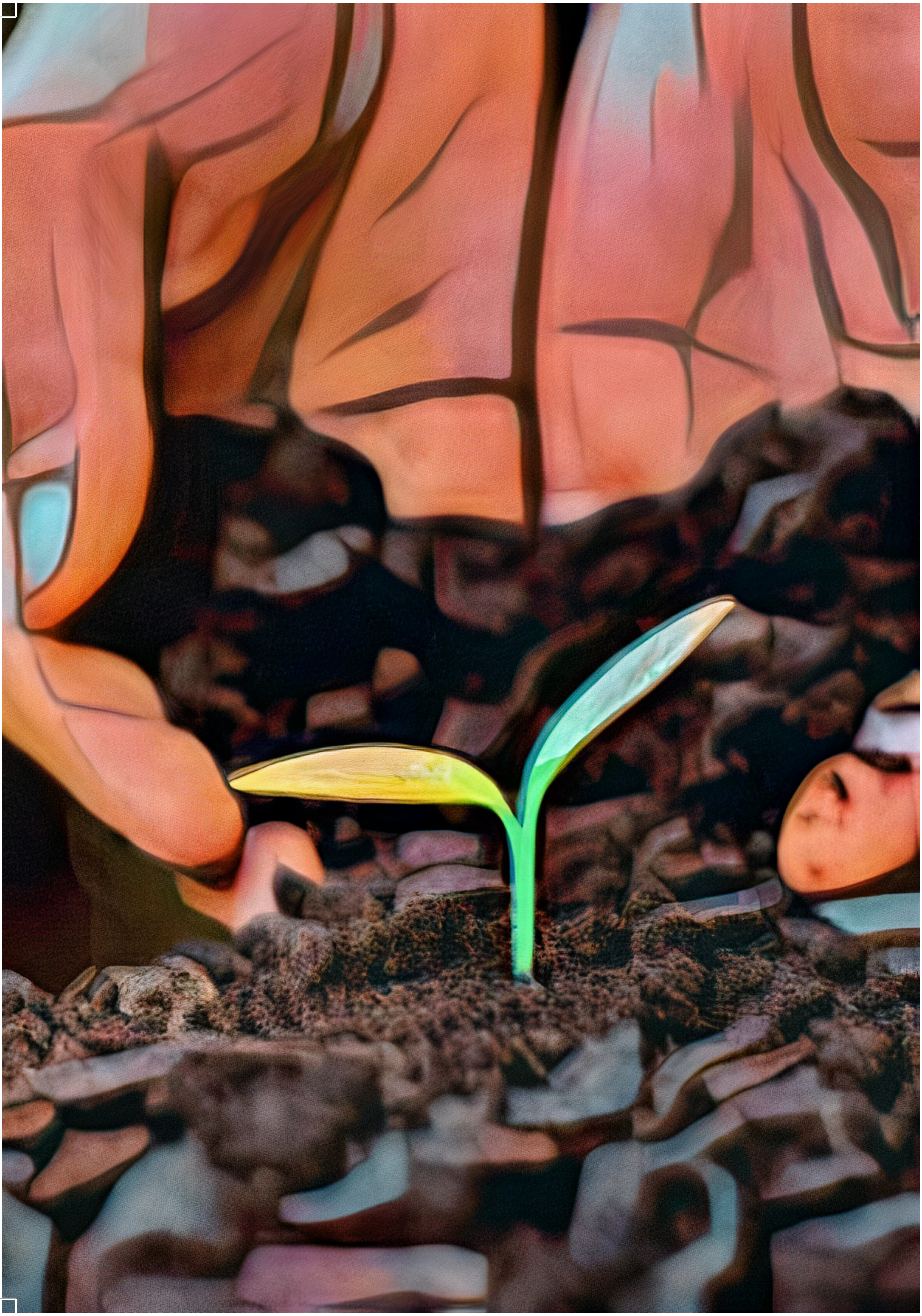

5. TREE COMMUNITIES IN 3-YR-OLD POST-MINING SITES UNDER DIFFERENT FOREST RESTORATION TECHNIQUES IN THE BRAZILIAN AMAZON

CHAPTER V

Tree communities in 3-yr-old post-mining sites under different forest restoration techniques in the Brazilian Amazon*

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ABSTRACT

Forest loss and degradation in the Brazilian Amazon due to mining activities has been intense over many years. To reverse this situation, a range of restoration programs of deforested and degraded areas have been created and implemented. The aim of this study was to analyze tree composition, successional stage, dispersal and pollination syndromes, conservation status of tree species, and proximity to seed sources under different forest restoration techniques (seedling planting, natural regeneration, and assisted natural regeneration or nucleation) implemented in post-mining sites in the Paragominas Municipality (Pará, Brazil). Sixty permanent plots with a restoration age of three years were selected for tree sampling. A total of 119 species, 83 genera and 27 botanical families were identified. Sites restored with different techniques significantly differed in tree composition. Seedling planting sites exhibited the highest abundance, species richness, and diversity values. These were less dominated by pioneer species when compared to the natural regeneration and nucleation sites. Entomophilic pollination and zoochory dispersal were highly represented in the three types of restored sites. Abundance and species richness were negatively correlated with distance from plots to seed sources, and they sharply declined in natural regeneration and nucleation plots at > 250 m from seed sources. Four threatened species were identified in the restored sites. We conclude that the combination of different restoration strategies at 3-year-old post-mining restoration sites in the Brazilian Amazon results in the recovery of considerable levels of local tree diversity.

Keywords: Dispersal; Importance Value Index; Pollination; Seed sources

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5.1. INTRODUCTION

The Brazilian Amazon rainforest contributes extensively to the world's biodiversity as it harbors ca. 16,000 tree species. Of this total, only 227 species are dominant, representing ca. half of all trees in the region; some 4,773 species are considered regulars, while 11,000 species representing only 0.12% of the trees are classified as rare [1]. Anthropogenic actions may drastically change the original forest landscape and drive many forest species to local extinctions [2–5]. Forests are suppressed by or highly disturbed for mineral extraction [6]. The impacts caused by mining can reach more than 10 km [7] due to factors such as land use change, urban expansion, waste discharge, and others [8–11]. Post-mining restoration has the potential to mitigate the impacts of mining activities on tropical biodiversity [12, 13], and assessment of restoration techniques is important for efficiency of resource use [14, 15].

Forest loss and degradation spreads over 788,353 km^2 in the Brazilian Amazon, of which 267,393 km^2 (40%) are in the Pará state and 8,792 km^2 (1%) in the Paragominas Municipality where our study was conducted [16]. Mining has significantly contributed to such forest loss and degradation. To redress this situation, a range of restoration programs on deforested and degraded areas were created and implemented in the region [17–21]. Restoration of post-mining areas in Brazil is under the regulation of federal Law 225 (1988 Federative Constitution of Brazil) and specific laws of each state [22]; there is though insufficient regulation of restoration projects and companies often fail to restore adequately (e.g. many restoration projects use exotic species, Cruz et al. [21]). Some results of post-mining restoration in the region have been previously published [23,24]. For instance, since the late 1970s the Mineração Rio do Norte SA company has developed a forest restoration program in Oriximiná municipality (Pará State), planting native forest species [25]. Planting a rich suite of native forest species is desirable for several reasons, including biodiversity conservation [19,26] and preventing establishment of exotic invasive species [27]. However, commercial timber species are often used due to their lower cost [28]. Restoration projects can be expensive and inefficient [29]; thus, there is an urgent need to implement adequate techniques for successful restoration projects [30,31].

The three major techniques applied to reestablish forest vegetation in post-mining sites are seedling planting [32–34], passive restoration or natural regeneration [35,36], and assisted natural regeneration by nucleation [37,38]. All these restoration techniques are ultimately linked to secondary succession [36], i.e. they both affect and are affected by this process. Active restoration involves management techniques such as planting that are aimed at producing a forest with a particular composition or structure; a wide variety of approaches have been used to restore degraded forest areas [39]. Natural regeneration involves the colonization of the sites to be restored by whatever plants and animals can disperse from surrounding habitats and subsequently establish; it therefore has a highly stochastic outcome [40]. Assisted natural regeneration represents an intermediate technique that involves acting in focal areas for facilitating vegetation recovery; nucleation, a type of assisted natural regeneration, pursues the establishment of woody recruits in these focal areas or nuclei to trigger forest expansion in larger areas over time through natural regeneration [41,42].

Knowledge of floristic composition is essential for all three types of restoration techniques for managing natural regeneration, selecting species to be used for restoration plantings and aiding conservation programs of threatened plant species [43–45]. The definition of functional groups of species that share similar traits has been shown to be a useful approach to understand secondary succession [46–49]. Assessing the functional composition trajectory may help overcome some limitations with taxonomic identification and provide more meaningful outcomes to evaluate restoration success [50]. Thus, the successional stage and the dispersal and pollination syndromes of the species involved in the restoration process, either planted or naturally established, are critical characteristics for both planning and assessing the outcomes of restoration projects [51–53]. For instance, habitat degradation disrupts key mutual interactions between animals and plants [5,54] and, consequently, affects seedling recruitment [55,56].

In this context, the present study aims to analyze the tree composition, the functional types (i.e. successional stage and the dispersal and pollination syndromes), the effect of distance between the restored sites and seed sources, and the conservation status of established tree species under different forest restoration techniques (namely seedling planting, natural regeneration, and nucleation) implemented in post-mining sites in the Paragominas municipality. Our starting hypothesis is that there are differences in tree composition and functional groups among the three forest recovery techniques (H1). We also hypothesized that distance from seed sources and vegetation recovery at the restored sites are negatively correlated (H2). We asked: *i)* Is tree diversity substantially recovered at post-mining sites in the early stages of restoration (Q1)?; *ii*) Is there a difference in species richness and diversity among the different restoration techniques (Q2)?; and *iii)* What is the conservation status of the species established under these techniques (Q3)? The answer to these questions and assessment of the formulated hypotheses will improve forest restoration of post-mining sites in the Brazilian Amazon and other tropical areas of the world.

5.2. MATERIAL AND METHODS

5.2.1. Characterization of the study area

The study was conducted in the Paragominas municipality (Figure 1), which is of 19,465 km^2 in area, and has a hot and humid climate, with annual an average temperature of 26.3ºC, relative air humidity of 81%, and annual average rainfall of 1,743 mm [57]. The region's soil is classified as a Yellow Dystrophic Latosol, with a very clayey texture (clay content > 700 g kg^{-1}). We collected data from the Degraded Area Recovery Program (PRAD) in the Hydro area of the Paragominas Mining Company S.A. (MPSA). The company owns an area of 18,668 ha of which 4,237 ha have been mined since 2006 and continues in full operation today. It extracts bauxite from 12 m deep mineral layers that results in suppressed vegetation and removal of topsoil and soil horizons. The disturbed mine sites to be revegetated are thus the unstructured soil horizons that were removed and used later to fill in the sites where bauxite was extracted. The PRAD in this area was established in 2009 and 2,339 ha had been recovered by 2019.

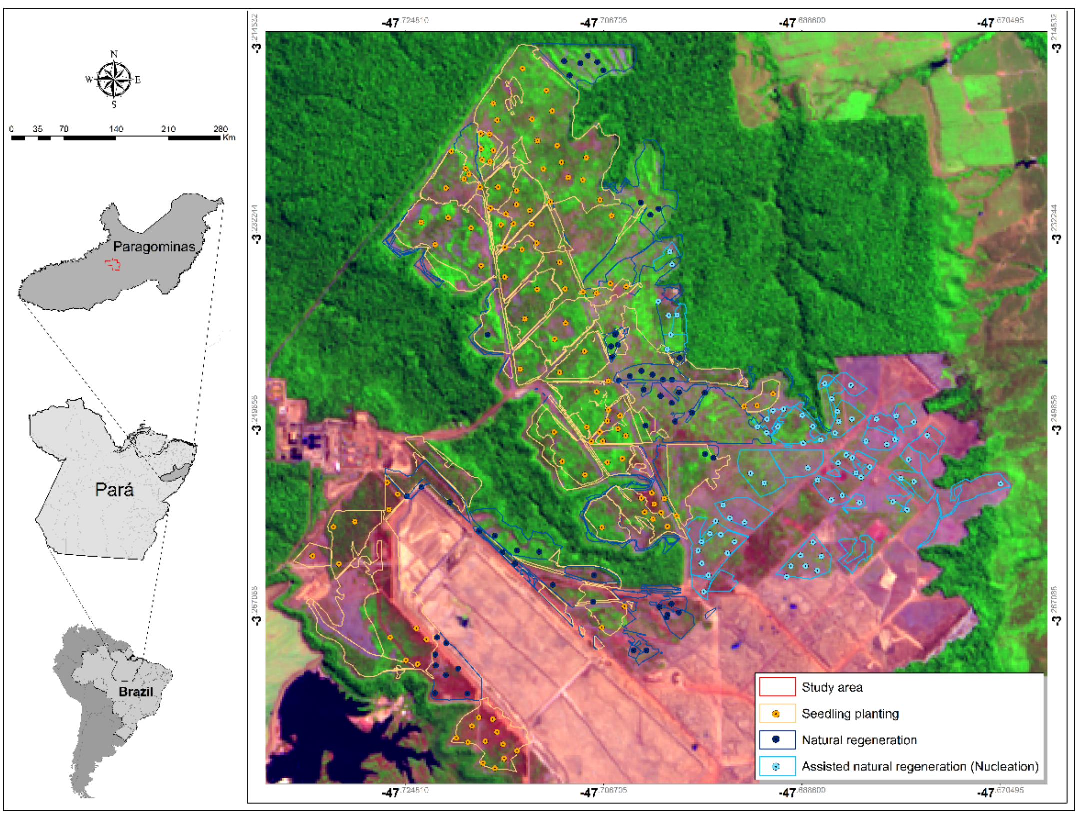

Figure 1. Location of the study area in Paragominas (Pará, Brazil), the three types of sites where post-mining restoration was implemented (seedling planting, natural regeneration and nucleation), and the 163 permanent plots established to assess distance to seed sources.

5.2.2. Forest restoration techniques

Post-mining restoration actions on the study area took place after mineral extraction finished in 2009. The first step towards forest restoration was topographic reshaping of the ground. This stage used sub-soiling with leveling grids (trawling), driven by low-compaction tire tractors to avoid laminar erosion and water accumulation. The second step was addition of a ca. 20-cm organic soil layer (the previously removed topsoil). This layer contained 25 m^3 ha^{-1} of non-timber residues such as leaves and litter in the plots to be restored by nucleation. This plant material was distributed as evenly as possible to provide adequate soil protection. Finally, the techniques that were used to restore forest vegetation were (a) seedling planting, (b) natural regeneration, and (c) nucleation (Figure 2).

(a) Seedling plantings comprised 120 tree species that are native to the region. The seedlings were produced in the nursery of the MPSA using seedling bags (15 x 20 cm) and tubes (6 x 19 cm) filled in with organic compost (manure and black earth in the proportion of 1:3). By the time of planting, they were on average 30 cm tall and 4-6 months old. A total of 1,111 seedlings ha^{-1} were planted on a regular spacing of 3 × 3 m in pits of 0.30 x 0.30 x 0.30 m, with a 90 gr N:P:K (20:10:20) and 500 g organic compost fertilization applied to each seedling once at the time of planting. The restoration using this technique started on an area of 92.48 ha in 2009 and attained 1,011 ha by 2016.

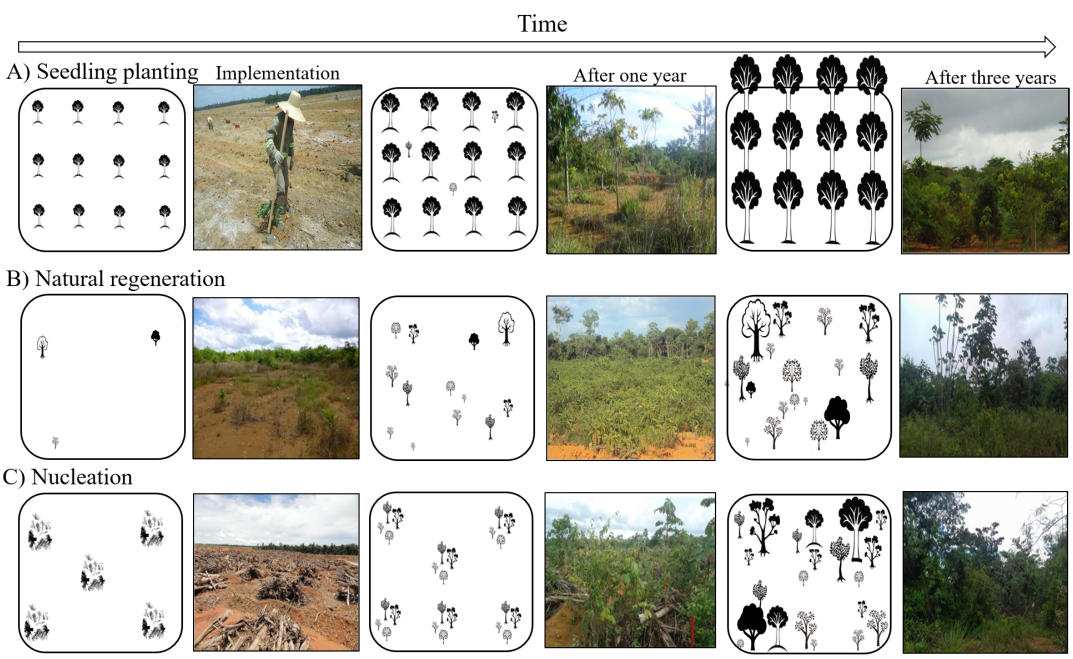

Figure 2. Sketch of the techniques that were used to restore forest vegetation in the studied post-mining sites and illustrative photos of the established vegetation over time.

(b) Natural regeneration occurred on the added topsoil after the topographic reshaping explained above. No chemical or biological treatment was applied. It commenced on 21 ha of post-mining area in 2009 and attained 546 ha by 2016.

(c) Nucleation used nuclei of residues (leaves, branches, stumps, etc.) from the suppressed vegetation on areas that would eventually be mined in the future in the company's land, which were transported to the previously leveled areas. These residues were arranged in mounds of 8-10 m^3, which formed a "chess board" layout intended to initiate the nucleation process. This technique started in 2013 on 9.16 ha and was later extended in 2014, 2015 and 2016 up to a total of 81.63 ha.

5.2.3. Data collection

A total of 163 permanent plots were established in the restored areas from 2009 to 2016, 83 at the seedling planting sites, 56 at the natural regeneration sites, and 24 at the nucleation sites (Table S1). They were 20 x 50 m (1,000 m^2) for the seedling planting and nucleation sites and 10 x 25 m (250 m^2) for the natural regeneration sites. All trees with diameter at breast height (dbh) $\geq$ 15 cm were surveyed for eight consecutive years between 2009 and 2016. We acknowledge that, by sampling only trees with dbh > 15 cm, many smaller trees were missed which undoubtedly contribute to the diversity in the studied sites, while the obtained results refer to only the most successfully, fast growing species. However, we only analyzed a subset of 60 plots with a restoration age of 3 years that were randomly selected (see below), namely 10 plots at the seedling planting sites, 10 at the nucleation sites, and 40 at the natural regeneration sites; the amount of plots at the nucleation sites was higher due to their smaller size, so the total area sampled was identical for the three restoration techniques.

To analyze tree composition at the restored sites, we calculated Importance Value Indices (IVI) of both species and families, which are based on relative frequency (number of plots where taxa occurred), relative density (number of individuals) and relative dominance (basal area across plots) (Table S2). The tree diversity was analyzed using the Shannon-Weaver, Simpson and Pielou Equability indices (Table S2).

The surveyed species list was classified into groups based on the successional stage labeled as pioneer (P), initial secondary (IS), late secondary (LS), and climax (C) species [58]. The IVI was also calculated for these successional stage groups. We adopted the morphological criteria defined by Pijl [59] to classify the species into the following types of dispersal syndrome: anemochory, autochory, barochory, hydrochory, and zoochory. The type of pollination was classified as anemophilic, entomophilic, melittophilic, chiropterophilic, and zoophilic according to Real [60] (Tables S3-S5).

We measured the distance between each restored plot and the nearest seed source. For this, an image of the Landsat-8 satellite (available at https://glovis.usgs.gov/app/, taken on 07/07/2018 with orbit/dot-223/62) was classified according to an unsupervised method to distinguish and delineate forest remnants around the restored sites. Then, the minimum distance of the plot to the nearest vegetation point was defined by the Euclidean distance method with ArcGIS 10.1 [61]. The distance between the plots and the nearest seed source was classified into three categories, namely short (< 250 m), intermediate (251–500 m) and long (> 501 m) distance.

Finally, the species were classified according to their conservation status or risk of extinction after the National Center for Flora Conservation (CNCFLORA; http://cncflora.jbrj.gov.br/portal/), which follows the guidelines, categories and criteria established by the IUCN (https://www.iucnredlist.org/). The nine groups were: LC (Least Concern), NT (Near Threatened), VU (Vulnerable), EN (Endangered), CR (Critically Endangered), EW (Extinct in the Wild), DD (Date Deficient), and NE (Not Evaluated).

5.2.4. Data analysis

A resampling technique was used to randomly select the 60 analyzed plots and ensure identical and comparable sampling areas among the different restoration types. This selection was repeated 1000 times, and the tree abundance, IVI and diversity indices were calculated on each occasion. Finally, we calculated the average and standard error of abundance, IVI and diversity indices with an alpha of 0.05 across all repetitions.

PERMANOVA [62] was used to test differences in tree composition, successional stage, and dispersal and pollination syndromes among sites restored with different techniques, with the R [63] vegan package [64]. A Multidimensional Scaling ordination (NMDS) [65], was used to visualize similarities among plots in terms of these characteristics, using the R MASS package [66]. The diversity indices were also calculated with the R vegan package. Finally, we correlated abundance and species richness and distance of each plot to the closest patch of remnant forest.

5.3. RESULTS

5.3.1. Tree composition at the restored sites

We observed 767 individual trees from 119 species, 83 genera and 27 botanical families within the 60 plots (3 ha in total) analyzed in this study. Of this total, 526 trees representing 101 species, 73 genera and 20 families occurred at seedling planting sites (Table S3); 155 trees, 14 species, 11 genera and 10 families at natural regeneration sites (Table S4); and 86 trees, 13 species, 10 genera and 8 families at nucleation sites (Table S5). Seedling planting plots exhibited the highest tree abundance (Table 1).

The species with highest IVI at seedling planting sites were *Protium* sp. (7.1% ± 0.16), *Inga alba* (Sw) Willd. (4.7% ± 0.07) and *Khaya ivorensis* A Chev. (4.6% ± 0.11) (Figure 3a); at natural regeneration sites they were *Croton matourensis* Aubl. (50.2% ± 0.19), *Solanum crinitum* Lam. (13.5% ± 0.1) and *Vismia guianensis* (Aubl.) Choisy. (10.2% ± 0.09) (Figure 3b); and at nucleation sites they were *Solanum crinitum* Lam. (25.7% ± 0.18), *Cecropia* sp.1 (21.4% ± 0.39) and *Cecropia distachya* Huber (19.1% ± 0.2) (Figure 3c). The families with highest IVI were Malpighiaceae, Euphorbiaceae and Urticaceae at each restoration type, respectively (Figure S1).

PERMANOVA showed that sites restored with different techniques significantly differed in their tree composition (Table 2a). Further, seedling planting sites were clearly segregated from the two other sites and the natural regeneration sites exhibited the highest variability, according to the NMDS (Figure 4a).

Table 1. Species richness and diversity indices (mean ± se) at post-mining restored sites. Different letter superscripts indicate statistically significant ($p < 0.05$) values between sites according to a Tukey's test.

Restoration Technique	Abundance	Richness	Diversity index		Pielou
			Shannon	Simpson	
Seedling planting	525 ± 2.71[a]	59.5 ± 0.36[a]	3.5 ± 0.01[a]	0.96 ± 0[a]	0.87 ± 0[a]
Natural regeneration	154 ± 0.6[b]	13.5 ± 0.04[b]	1.5 ± 0.01[b]	0.64 ± 0[b]	0.59 ± 0[b]
Nucleation	85.7 ± 0.81[b]	11.3 ± 0.15[b]	1.9 ± 0.01[c]	0.81 ± 0[b]	0.8 ± 0[b]

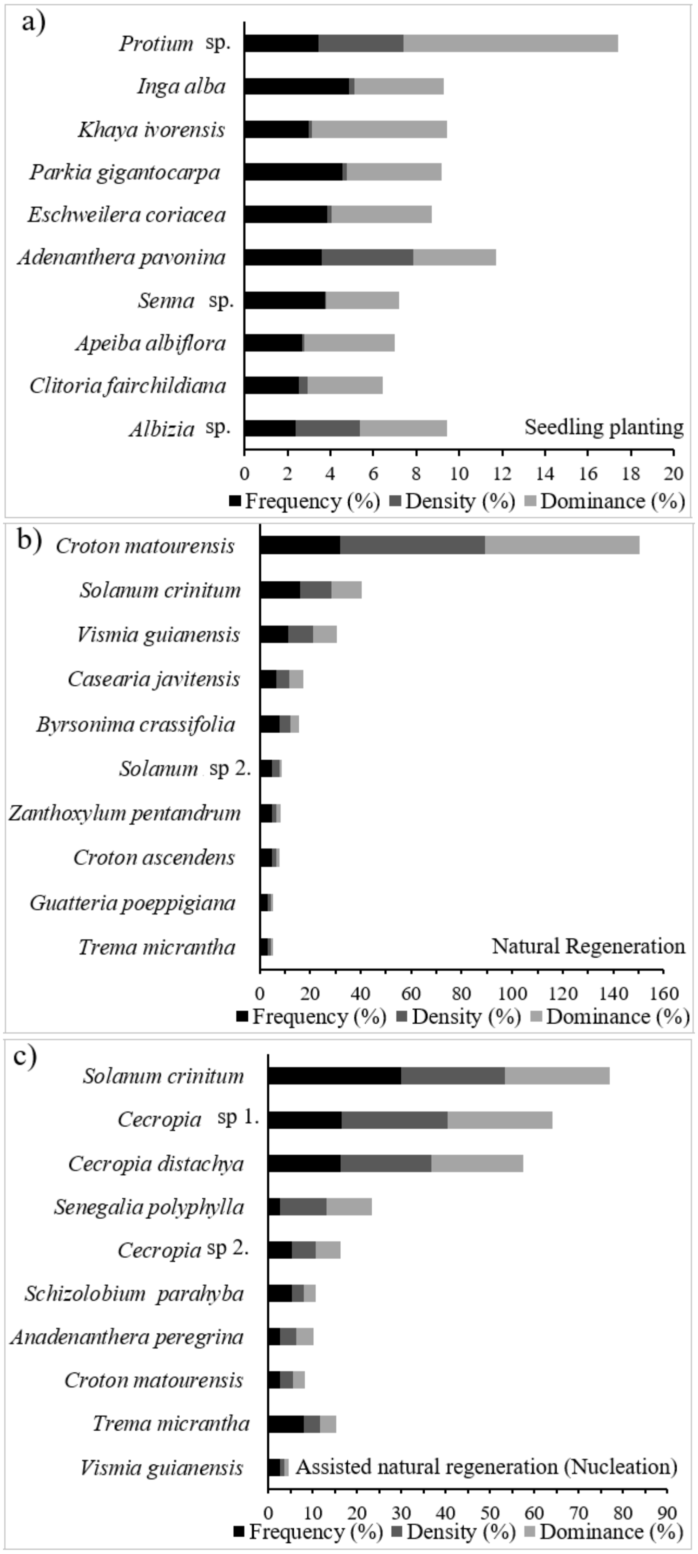

Figure 3. Relative frequency, density and dominance of the species with highest IVI (i.e. the sum of these three components) at the seedling planting (a), natural regeneration (b) and nucleation (c) sites.

Table 2. PERMANOVA of (a) tree species composition, (b) successional status and (c) dispersal and (d) pollination syndromes among post-mining restoration types.

(a)	**Tree species composition**					
	df	*SS*	*MS*	*F.Model*	*R2*	*Pr(>F)*
Techniques	2	8.582	4.2909	11.808	0.1926	0.001***
Residuals	99	35.976	0.3634		0.8074	
Total	101	44.558			1.0000	
(b)	**Successional status**					
	Df	*SS*	*MS*	*F.Model*	*R2*	*Pr(>F)*
Techniques	2	12.851	6.4254	47.329	0.48879	0.001***
Residuals	99	13.440	0.1358		0.51121	
Total	101	26.291			1.00000	
(c)	**Dispersal syndrome**					
	df	*SS*	*MS*	*F.Model*	*R2*	*Pr(>F)*
Techniques	2	12.732	6.3658	32.195	0.39409	0.001***
Residuals	99	19.575	0.1977		0.60591	
Total	101	32.306			1.00000	
(d)	**Pollination syndrome**					
	df	*SS*	*MS*	*F.Model*	*R2*	*Pr(>F)*
Techniques	2	16.085	8.0423	48.965	0.49728	0.001***
Residuals	99	16.260	0.1642		0.50272	
Total	101	32.345			1.00000	

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’

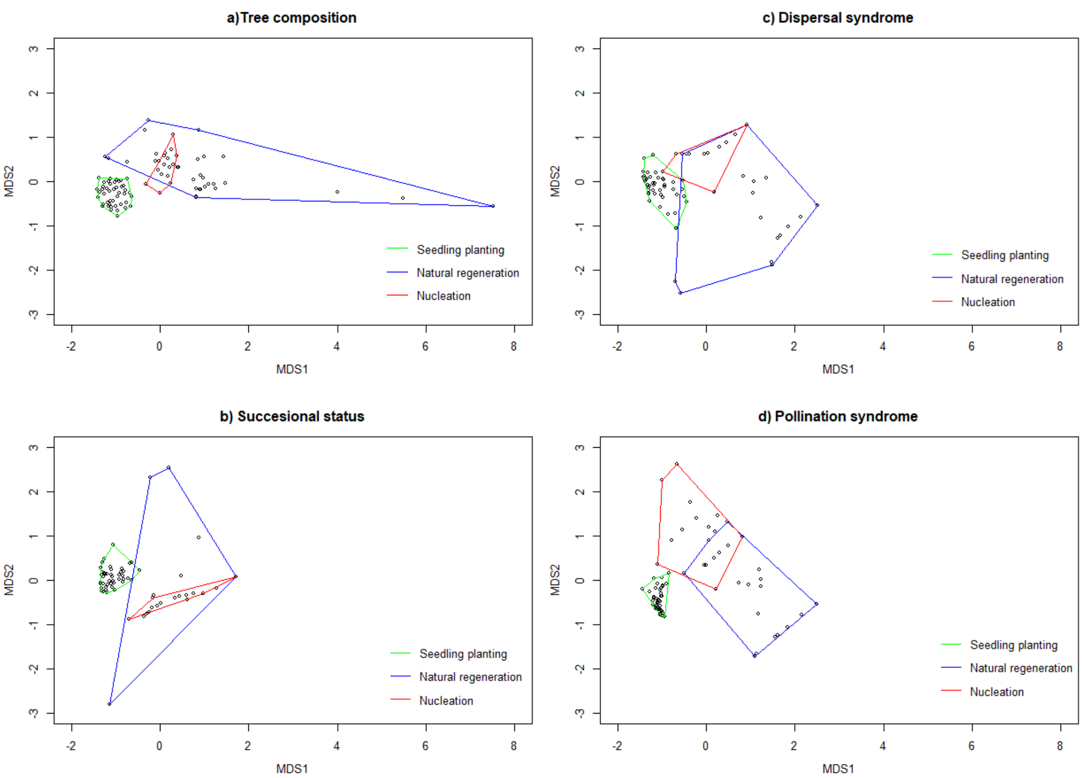

Figure 4. Plot ordination of (a) tree composition, (b) successional status, (c) dispersal syndrome, and (d) pollination syndrome under seedling planting, natural regeneration and nucleation techniques according to a NMDS.

5.3.2. Species richness and diversity

Seedling planting sites exhibited the highest species richness, Shannon, Simpson, and Pielou index values, whereas the diversity values found in nucleation sites were slightly greater than in natural regeneration sites (Table 1).

5.3.3. Functional types

PERMANOVA showed that successional status, dispersal and pollination syndromes significantly differed among sites restored with different techniques (Table 2b-d). Again, seedling planting sites were clearly segregated from the two other sites and the natural regeneration sites were the most widely spread on the NMDS plot (Figure 4b-d).

The majority of species identified were categorized in the pioneer group (41), followed by the initial secondary (37), late secondary (39), and climax (2) groups. Nucleation (92% ± 0.2) and natural regeneration (87% ± 0.1) sites showed higher pioneer IVI than seedling planting sites (30% ± 0.2) (Table S6). Initial secondary (25% ± 0.2) and late secondary (42% ± 0.2) species were the most prominent in the seedling planting sites and of marginal importance in the natural regeneration (6% ± 0.1 and 7% ± 0.1, respectively) and nucleation (5% ± 0.2 and 2% ± 0.2, respectively) sites.

The surveyed species were classified as zoocoric (56%), autocoric (21%), anemocoric (17%), barocoric (4%), and hydrocoric (2%) according to their dispersal syndrome. The three types of restoration sites were dominated by zooric species followed by autocoric species, whereas anemocoric species were also relevant in the seedling planting sites (Figure 5a).

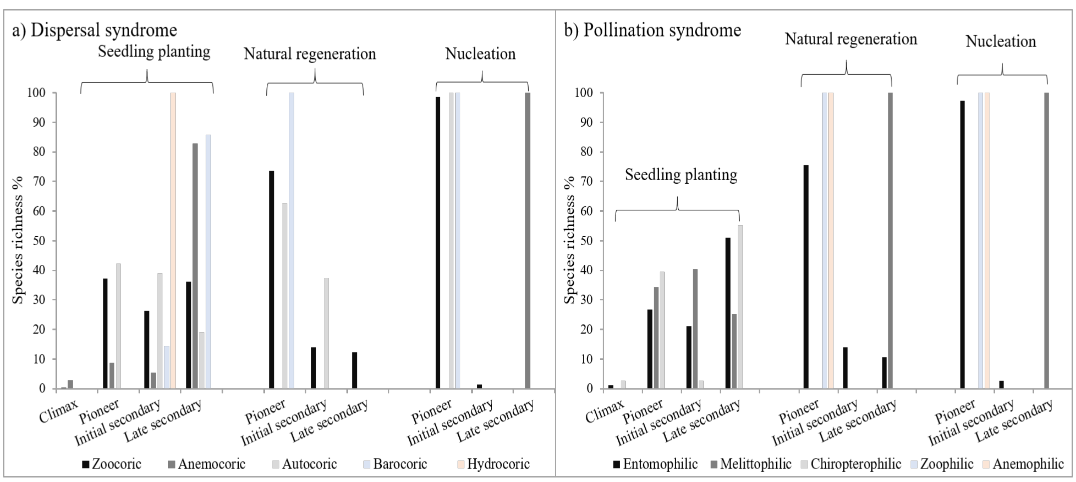

Figure 5. Proportion of species according to the (a) dispersal and (b) pollination syndromes in seedling planting, natural regeneration and nucleation sites.

Most species were classified as entomophilic (72%), which were followed by meliophilic (19%), anemophilic (5%), zoophilic (3%), and chiropterophilic (1%) species. The entomophilic syndrome dominated the three restoration techniques, and the meliophilic and anemophilic syndromes were also relevant at natural regeneration and nucleation sites, respectively (Figure 5b).

5.3.4. Effects of distance to seed sources

Tree abundance and species richness at the restored plots were negatively correlated with distance to the seed sources under the three restoration techniques (Figure 6). The seedling planting plots exhibited the highest correlation coefficients and the nucleation plots the lowest. Noticeably, abundance and species richness gradually declined with distance to forest edge at the seedling planting sites. However, both nucleation and natural regeneration sites exhibited a sharp decline of abundance and species richness along the shortest distances (< 250 m) from seed sources; abundance and richness were very low and remain constant at distances > 250 m.

The majority of tree species that were established close (< 250 m) to seed sources were mostly of zoochory dispersal (45% in seedling planting, 93% in natural regeneration, 69% in nucleation plots) and entomophilic pollination (87% in seedling planting; 64% in natural regeneration; 62% in nucleation plots). Regarding the successional status, 44% of the species in the seedling planting sites were late secondary, whereas 79% and 77% were pioneers in the natural regeneration and nucleation sites, respectively.

5.3.5. Conservation status

Only 11 species found in this study have been evaluated by the National Center for Plant Conservation and all of them were planted. Four species were threatened and assigned to the categories VU (*Swietenia macrophylla* King., *Hymenaea parvifolia* Huber and *Cedrela fissilis* Vel. L) and EN (*Vouacapoua americana* Aubl.). The LC category was represented by *Pterocarpus santalinoides* L'Hér. Ex DC., *Bowdichia nitida* Spruce ex Benth., *Lecythis lurida* (Miers) S.A. Mori., *Hymenaea courbaril* L., and *Genipa americana* L., the NT category by *Handroanthus impetiginosus* (Mart. Ex DC.) Mattos., and the DD category by *Ficus malacocarpa* Standl.

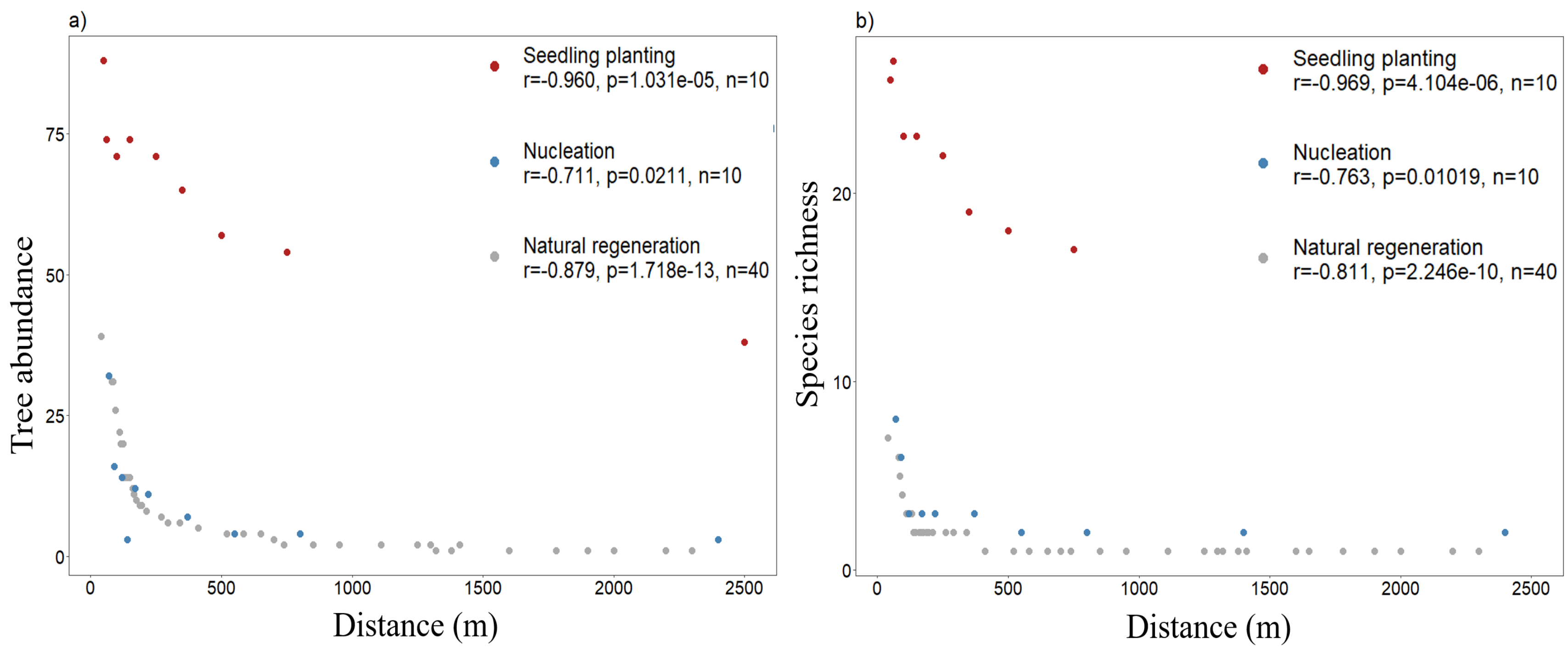

Figure 6. Tree abundance (a) and species richness (b) in the assessed plots at post-mining restored sites located at different distance from seed sources.

5.4. DISCUSSION

This study assessed the outcomes of contrasting forest restoration techniques in terms of tree composition, functional types, and conservation value of the established tree species in Amazonian 3-year-old post-mining sites. Overall, our results support our starting hypothesis on the differences in tree composition and functional groups among the three forest recovery techniques (H1). We also found an acceleration of vegetation recovery for sites close to seed sources (H2), a substantial level of early established tree species (Q1), differences in species richness and diversity among the different restoration techniques (Q2), and a few endangered tree species established in the young restored sites (Q3).

5.4.1. Effects of restoration techniques on tree community

We found that sites restored with different techniques differed in tree composition. The success in establishing a forest restoration project depends, among other factors, on the selection of the techniques to be implemented [29,31,40,67]. This selection should consider context factors such as the level of initial degradation, the characteristics of the landscape and the reference community, that is the subject of restoration [67–70]. A current debate is to what extent it is justified to use active restoration techniques such as seedling planting over passive restoration as the former is much more expensive than the latter [36,50]. This debate has been fueled by recent global meta-analyses related to forest restoration, which have found that recovery levels of biodiversity, forest structure and function indicators are often greater, or at least similar, for passive restoration than for active restoration in the long term [29,71,72]. However, the current study, seedling planting sites exhibited the highest abundance, species richness, and diversity values. This finding can be attributed to the high initial degradation level of post-mining sites, in accordance with Reid *et al.* [73] who found a positive site selection bias in meta-analyses comparing natural regeneration to active forest restoration (i.e. passive restoration outperforms or is similar to than active restoration because passively restored sites tend to be less disturbed than those sites restored by active restoration techniques).

Key constraints for vegetation recovery are: (1) seed bank availability and germination [74]; (2) dispersal limitation, because seed sources in restoration sites include remote and dispersal vectors may be rare [75]; (3) abiotic limitation, such as low water availability, extreme temperatures, poor soil structure, and low nutrient availability [76–78]; and (4) biotic limitations, such as competition from herbaceous vegetation and herbivory [79,80]. In this study, community composition and the features of taxa at the three types of restored sites indicates that seedling planting mitigates the constraints for natural regeneration. Thus, the dominant families and species with highest IVI, overall tree composition, and most relevant functional types according to the successional status were notably different in the seedling planting sites, which were less dominated by pioneer species, when compared to the natural regeneration and nucleation sites. However, the dispersal and pollination syndromes mostly overlapped across all restoration types as in the tropics most dispersal is zoochory [81] and most pollination is by insects [82,83]. The dispersal of plots in our NMDS analyses reflects the high stochasticity of restoration outcomes following natural regeneration [84,85] and the more predictable outcomes of seedling plantings [86,87]. Nucleation sites performed as reduced subsets of the natural regeneration sites, still more similar to the seedling planted sites, probably because nucleation only intervened in the soil and did not plant or seed trees.

Not surprisingly, the most abundant and species-rich family in our study was Fabaceae, which has high ecological plasticity and a high capacity of nitrogen fixation and facilitates the establishment of other species [88]. Gama *et al.* [89] showed that *Guatteria poeppigiana* Mart. and *Manihot brachyloba* Müll. Arg., which were identified in the natural regeneration sites of this study, have high potential for restoring degraded areas. In the nucleation sites, on top of the natural recovery progress, the nuclei create microhabitats that facilitate the entry of several plant species into the system [42,90]. Species such as *Cecropia distachya* Huber and *Solanum crinitum* Lam, which were present in the nucleation sites, are also considered as important for the recovery of degraded areas [91].

5.4.2. Proximity to seed sources accelerates vegetation recovery

We found that both abundance and species richness and distance to seed sources were negatively correlated across all restored sites, as Cubiña [92] also reported, meaning that proximity to seed sources accelerates vegetation recovery. This well-known pattern [93,94] supports the necessity of conserving forest remnants within and around mining projects to assure a high seed pressure [23,95,96], and the utility of planting tree islands that eventually may trigger applied nucleation [42,97]. In central Amazonia, abundance and species richness have been found to be affected at distances between 10 to 400 m from the fragment edges [98].

Our results detected that natural regeneration is severely limited at distances > 250 m in the natural regeneration and nucleation sites, in agreement with other studies [94,99,100]. Some studies have shown that geographical distance influences the distribution of plants in the tropics, and that the variation in richness and species composition in a given region is limited by seed dispersal [101,102]. At restored sites in the proximities of forest edges, there may be a higher abundance of pioneers and initial secondary species established from the seed bank contained on the topsoil [103].

5.4.3. Relevance for biodiversity conservation

Our study provides further evidence that restoration is a tool for biodiversity conservation [68,104,105]. Thus, a total of 119 species, 83 genera and 27 botanical families were identified in 30 ha of a 3-year-old restored mined area. Similarly, Rankin-de-Merona *et al.* [106] found 53 botanical families in a survey of 70 ha in the Amazonian rainforest close to Manaus. Other studies have reported a substantial recovery of biodiversity in post-mining restoration sites around the world [80,107–112]. Further, we found quick establishment of threatened tree species. This is of particular importance in biodiversity hotspots such as the Amazonian rainforest, where it is estimated that between 5% and 9% of all species will be threatened with extinction by 2050 [2].

5.5. CONCLUSIONS

Our study has shown that (1) a substantial amount of local tree diversity was recovered in young post-mining restored sites in the Brazilian Amazon rainforest (119 species, 83 genera and 27 botanical families). However, (2) sites restored with different techniques showed significantly different tree composition (e.g. they were dominated by Fabaceae at seedling plantings, Euphorbiaceae at natural regeneration sites, and Urticaceae at nucleation sites). Further, the restoration sites also (3) differed in their abundance, species richness, and diversity values, which were highest at the seedling planting sites, and functional groups based on the successional status and dispersal and pollination syndromes. Thus, seedling planting sites were less dominated by pioneer species compared to the natural regeneration and nucleation sites, whereas entomophilic pollination and zoochory dispersal were highly represented at the three types of restored sites. Abundance and species richness (5) were negatively correlated with distance of plots to seed sources. However, whereas these values sharply declined in natural regeneration and nucleation plots at > 250 m from seed sources, they were more constant in seedling planting sites. Noticeably, (6) four threatened species were identified in the restored sites. Overall, the combination of different restoration strategies at 3-year-old post-mining restoration sites resulted in considerable levels of recovery of local tree diversity.

SUPPLEMENTARY MATERIALS INFORMATION

The following are available online at www.mdpi.com/link, Figure S1: Mean Importance Value Indices for each botanical family found at seedling planting, natural regeneration, and nucleation sites., Table S1: Implementation of forest restoration plots, Table S2: Phytosociological analysis of vegetation structure, Table S3: Species list at the seedling planting sites with phytosociological values, dispersal and pollination syndromes, and successional group (PI = Pioneers species; IS = Initial secondary species; LS = Late secondary and CL = Climax species), Table S4: Species list at the natural regeneration sites with phytosociological values, dispersal and pollination syndromes, and successional group (PI = Pioneers species; IS = Initial secondary species; LS = Late secondary and CL = Climax species), Table S5: Species list at the nucleation sites with phytosociological values, dispersal and pollination syndromes, and successional group (PI = Pioneers species; IS = Initial secondary species; LS = Late secondary and CL = Climax species), Table S6: Phytosociological analyses of the ecological groups in the seedling planting, natural regeneration and nucleation sites.

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SUPPORTING INFORMATION

Table S1. Implementation of forest restoration plots.

Year	Seedling planting		Natural regeneration		Assisted natural regeneration	
	Area (ha)	Number of Plots	Area (ha)	Number of Plots	Area (ha)	Number of Plots
2009	71.44	6	21.04	3	-	-
2010	61.96	6	49.74	2	-	-
2011	123.23	12	4.45	4	-	-
2012	74.75	6	191.96	22	-	-
2013	99.1	10	-	-	9.19	4
2014	240.36	10	238.6	23	44.78	13
2015	218.15	21	31.87	1	27.66	7
2016	122.03	12	8.32	1	-	-
Total	1,011.02	83	545.98	56	81.63	24

Source: Elaborated by authors, data from MPSA.

Table S2. Phytosociological analysis of vegetation structure.

Parameters	Formula	Description
Frequency	$Fa_i = \frac{\text{Samples units number with the species}}{\text{total sample units number}} .100$ $Fr_i = \frac{Fa_i}{\sum_{i=1}^{S} Fa_i} .100$	Absolute Frequency (Fai) Relative Frequency (Fri)
Abundance	$Ar_i = n^o\, árv.ha^{-1}$ $Ar_i = \frac{Aa_i}{\sum_{i=1}^{S} Aai} .100$	Absolute Abundance (Aai) Relative Abundance (Ari)
Dominance	$Da_i = \sum_{i=1} g_i$ $Dr_i = \frac{Da_i}{\sum_{i=1}^{S} Da_i} .100$	Absolute Dominance (Dai) Relative Dominance (Dri)
Importance Value Index	$IVI = Fr_i + Ar_i + DoR_i$	Sum of relative values of the abundance, dominance and frequency.
Shannon-Weaver (H') Index	$H' = \frac{[DT \ln(DT) - \sum_{i=1}^{s} DA_i \ln(DA_i)]}{DT}$	H'= Shannon-Weaver diversity indices; DT = Total density; DAi = Absolute density of the i species.
Simpson Index	$C = \frac{[\sum_{i=1}^{S} DAi(DAi - 1)]}{[DT(DT-1)]}$	Probability of two individuals chosen independently and at random in the same community belong to the same species.
Pielou equability indices	$H'_{máx} = \ln(s)$ $E = \frac{H'}{H'máx}$	Proportion of the diversity observed in relation to the maximum expected diversity. H '= Shannon-Weaver Index; S = total number of species sampled.

Table S3. Species list at the seedling planting sites with phytosociological values, pollination and dispersal syndromes, and successional group (SG, PI = Pioneers species; IS = Initial secondary species; LS = Late secondary; CL = Climax species).

Famíly	Species	No.	AR	FR	DoR	IVI	Pollination	Dispersal	SG
Fabaceae	*Protium* sp.	20.75 ± 0.5	3.94 ± 0.09	3.46 ± 0.07	9.99 ± 0.22	7.14 ± 0.16	Entomophilic	Zoochory	LS
Arecaceae	*Inga alba* (Sw.) Willd.	1.39 ± 0.12	0.27 ± 0.02	4.86 ± 0.05	4.15 ± 0.09	4.73 ± 0.07	Entomophilic	Zoochory	IS
Fabaceae	*Khaya ivorensis* A. Chev.	1 ± 0.12	0.19 ± 0.02	2.97 ± 0.06	6.28 ± 0.17	4.63 ± 0.11	Entomophilic	Anemochory	IS
Malvaceae	*Parkia gigantocarpa* Ducke.	1.04 ± 0.08	0.2 ± 0.02	4.55 ± 0.05	4.44 ± 0.11	4.54 ± 0.07	Entomophilic	Zoochory	LS
Lecythidaceae	*Eschweilera coriacea* (DC.) S.A Mori	1.09 ± 0.13	0.21 ± 0.02	3.84 ± 0.07	4.67 ± 0.16	4.43 ± 0.12	Melittophilic	Zoochory	LS
Fabaceae	*Adenanthera pavonina* L.	22.44 ± 0.56	4.24 ± 0.1	3.61 ± 0.05	3.86 ± 0.12	3.9 ± 0.08	Entomophilic	Autochory	IS
Malvaceae	*Senna* sp.	0.24 ± 0.03	0.04 ± 0.01	3.76 ± 0.06	3.39 ± 0.1	3.7 ± 0.08	Entomophilic	Autochory	PI
Bignoniaceae	*Apeiba albiflora* Ducke	0.46 ± 0.04	0.09 ± 0.01	2.69 ± 0.06	4.22 ± 0.13	3.33 ± 0.09	Melittophilic	Zoochory	IS
Fabaceae	*Clitoria fairchildiana* R.A. Howard.	2.1 ± 0.14	0.4 ± 0.03	2.52 ± 0.05	3.52 ± 0.15	3.23 ± 0.11	Entomophilic	Autochory	PI
Fabaceae	*Albizia* sp.	15.64 ± 0.5	2.98 ± 0.1	2.39 ± 0.06	4.07 ± 0.13	3.14 ± 0.09	Entomophilic	Autochory	LS
Bignoniaceae	*Astronium lecointei* Ducke.	0.22 ± 0.03	0.04 ± 0	3.05 ± 0.06	2.98 ± 0.09	3.11 ± 0.07	Entomophilic	Anemochory	LS
Fabaceae	*Bauhinia acreana* Harms.	0.47 ± 0.05	0.09 ± 0.01	2.07 ± 0.06	4.03 ± 0.14	2.93 ± 0.09	Entomophilic	Autochory	IS
Fabaceae	*Acacia polyphylla* DC.	18.28 ± 0.7	3.44 ± 0.13	1.99 ± 0.05	3.28 ± 0.15	2.9 ± 0.1	Melittophilic	Autochory	PI
Fabaceae	*Schizolobium parahyba* var. *amazonicum* (Huber ex.Ducke) Barneby.	17.3 ± 0.43	3.31 ± 0.08	2.33 ± 0.05	2.17 ± 0.09	2.66 ± 0.08	Entomophilic	Zoochory	PI
Fabaceae	*Tamarindus indica* L.	2.34 ± 0.14	0.44 ± 0.03	3.29 ± 0.06	2.38 ± 0.06	2.64 ± 0.05	Entomophilic	Zoochory	IS
Burseraceae	*Caesalpinia pyramidalis* var. diversifolia Benth.	0.69 ± 0.08	0.13 ± 0.02	2.15 ± 0.06	2.73 ± 0.15	2.45 ± 0.11	Entomophilic	Autochory	PI

Chrysobalanaceae	*Piptadenia peregrina* (L.) Benth.	0.23 ± 0.03	0.04 ± 0	2.62 ± 0.06	2.2 ± 0.12	2.38 ± 0.08	Entomophilic	Autochory	IS
Fabaceae	*Handroanthus serratifolius* (A.H.Gentry) S.Grose.	12.25 ± 0.45	2.31 ± 0.08	1.92 ± 0.06	2.21 ± 0.11	2.32 ± 0.09	Entomophilic	Anemochory	LS
Moraceae	*Pterocarpus santalinoides* L'Hér. ex.DC.	1.13 ± 0.09	0.22 ± 0.02	2.56 ± 0.06	1.98 ± 0.07	2.1 ± 0.06	Entomophilic	Hydrochory	IS
Meliaceae	*Bauhinia rufa* (Bong) Steud.	2.72 ± 0.12	0.52 ± 0.02	2.62 ± 0.05	1.7 ± 0.07	2.06 ± 0.05	Entomophilic	Autochory	IS
Annonaceae	*Annona muricata* L.	7.79 ± 0.31	1.47 ± 0.06	1.72 ± 0.05	1.94 ± 0.07	1.71 ± 0.06	Entomophilic	Zoochory	IS
Euphorbiaceae	*Ceiba pentandra* (L.) Gaertn.	14.73 ± 0.54	2.83 ± 0.11	1.42 ± 0.05	1.41 ± 0.09	1.47 ± 0.06	Melittophilic	Anemochory	LS
Meliaceae	Inga edulis Mart.	1.6 ± 0.11	0.3 ± 0.02	1.17 ± 0.05	1.6 ± 0.08	1.31 ± 0.06	Entomophilic	Zoochory	LS
Bignoniaceae	*Lophanthera lactescens* Ducke.	9.83 ± 0.35	1.85 ± 0.06	1.39 ± 0.04	1.1 ± 0.06	1.23 ± 0.05	Entomophilic	Autochory	IS
Malvaceae	*Parkia nitida* Miq.	0.46 ± 0.05	0.08 ± 0.01	1.25 ± 0.05	1.06 ± 0.05	1.19 ± 0.05	Entomophilic	Zoochory	LS
Fabaceae	*Cedrela fissilis* Vell.	4.89 ± 0.29	0.92 ± 0.05	1.1 ± 0.04	1.04 ± 0.06	1.1 ± 0.05	Entomophilic	Anemochory	CL
Fabaceae	*Vouacapoua americana* Aubl.	0.69 ± 0.05	0.13 ± 0.01	1.25 ± 0.05	0.79 ± 0.07	1.07 ± 0.05	Entomophilic	Zoochory	LS
Anacardiaceae	*Anacardium occidentale* L.	5.07 ± 0.26	0.97 ± 0.05	1.13 ± 0.04	1.07 ± 0.07	1.06 ± 0.05	Entomophilic	Zoochory	LS
Meliaceae	*Sterculia apetala* var. *elata* (Ducke) E.L. Taylor ex.Brako & Zarucchi.	5.92 ± 0.26	1.12 ± 0.05	1.46 ± 0.05	0.95 ± 0.04	1.04 ± 0.04	Melittophilic	Zoochory	IS
Fabaceae	*Oenocarpus distichus* Mart.	1.34 ± 0.09	0.26 ± 0.02	0.94 ± 0.04	1.28 ± 0.06	1.02 ± 0.05	Entomophilic	Zoochory	IS
Fabaceae	*Machaerium hirtum (*Vell.*)* Stellfeld	0.24 ± 0.03	0.04 ± 0	1.24 ± 0.04	0.47 ± 0.03	0.94 ± 0.04	Entomophilic	Anemochory	IS
Lecythidaceae	*Handroanthus ochraceus* (Cham.) Mattos	3.66 ± 0.23	0.68 ± 0.04	1.2 ± 0.05	0.25 ± 0.02	0.79 ± 0.03	Entomophilic	Anemochory	LS
Fabaceae	*Parkia* sp.	9.19 ± 0.28	1.77 ± 0.06	0.63 ± 0.03	0.96 ± 0.06	0.76 ± 0.04	Entomophilic	Zoochory	LS

Boraginaceae	*Enterolobium schomburgkii* (Benth.) Benth.	6.39 ± 0.27	1.2 ± 0.05	1.07 ± 0.04	0.45 ± 0.03	0.71 ± 0.03	Melittophilic	Barochory	LS
Fabaceae	*Eschweilera* sp.	0.44 ± 0.04	0.09 ± 0.01	0.93 ± 0.04	0.64 ± 0.04	0.71 ± 0.03	Melittophilic	Zoochory	LS
Fabaceae	*Senegalia polyphylla* (DC.) Britton & Rose	14.09 ± 0.49	2.7 ± 0.1	1.09 ± 0.05	0.6 ± 0.03	0.71 ± 0.03	Entomophilic	Autochory	PI
Fabaceae	*Carapa guianensis* Aubl.	3.16 ± 0.16	0.6 ± 0.03	1.08 ± 0.04	0.47 ± 0.03	0.69 ± 0.03	Entomophilic	Hydrochory	IS
Malpighiaceae	*Andira inermis* (W. Wright) DC.	4.5 ± 0.23	0.85 ± 0.04	1.07 ± 0.04	0.11 ± 0.01	0.68 ± 0.03	Melittophilic	Zoochory	PI
Fabaceae	*Samanea tubulosa* (Benth.) Barneby & J.W.Grimes.	11.84 ± 0.28	2.25 ± 0.05	0.9 ± 0.04	0.46 ± 0.02	0.68 ± 0.03	Entomophilic	Anemochory	PI
Fabaceae	*Lecythis lurida* (Miers) S.A Mori	1.8 ± 0.12	0.34 ± 0.02	0.93 ± 0.04	0.19 ± 0.02	0.63 ± 0.03	Melittophilic	Autochory	LS
Lecythidaceae	*Lecythis pisonis* Cambess.	0.44 ± 0.05	0.08 ± 0.01	0.62 ± 0.03	0.43 ± 0.03	0.5 ± 0.03	Entomophilic	Autochory	LS
Rubiaceae	*Hevea brasiliensis* (Willd ex.A. Juss.) Müll.Arg.	3.61 ± 0.19	0.68 ± 0.04	0.63 ± 0.03	0.34 ± 0.03	0.48 ± 0.03	Entomophilic	Autochory	LS
Malvaceae	*Inga fagifolia* (L.) Willd. ex.Benth.	0.46 ± 0.04	0.09 ± 0.01	0.62 ± 0.03	0.41 ± 0.04	0.48 ± 0.03	Entomophilic	Zoochory	IS
Lecythidaceae	*Handroanthus* sp.	41.92 ± 1.09	7.96 ± 0.2	0.66 ± 0.04	0.41 ± 0.03	0.46 ± 0.03	Entomophilic	Anemochory	LS
Malvaceae	*Parinari excelsa* Sabine.	1.37 ± 0.07	0.27 ± 0.01	0.6 ± 0.03	0.24 ± 0.02	0.44 ± 0.03	Entomophilic	Zoochory	LS
Euphorbiaceae	*Libidibia ferrea* (Mart.) L.P Queiroz.	6.08 ± 0.34	1.16 ± 0.06	0.79 ± 0.04	0.22 ± 0.01	0.43 ± 0.02	Entomophilic	Autochory	PI
Fabaceae	*Genipa americana* L.	24.41 ± 0.5	4.63 ± 0.09	0.31 ± 0.02	0.52 ± 0.05	0.41 ± 0.04	Entomophilic	Zoochory	PI
Fabaceae	*Swartzia* sp.	0.92 ± 0.06	0.17 ± 0.01	0.62 ± 0.03	0.14 ± 0.01	0.37 ± 0.02	Entomophilic	Zoochory	PI
Moraceae	*Cassia fistula* L.	2.1 ± 0.19	0.39 ± 0.04	0.16 ± 0.02	0.54 ± 0.06	0.36 ± 0.04	Entomophilic	Zoochory	IS
Fabaceae	*Byrsonimia densa* (Poir) DC.	0.22 ± 0.03	0.04 ± 0.01	0.6 ± 0.03	0.16 ± 0.01	0.35 ± 0.02	Entomophilic	Zoochory	LS
Anacardiaceae	*Handroanthus impetiginosus* (Mart. Ex.DC.) Mattos.	6.63 ± 0.29	1.26 ± 0.05	0.46 ± 0.03	0.34 ± 0.03	0.35 ± 0.02	Entomophilic	Anemochory	LS

Anacardiaceae	*Bauhinia platypetala* Burch. Ex Benth.	1.16 ± 0.09	0.22 ± 0.02	0.5 ± 0.03	0.29 ± 0.03	0.33 ± 0.02	Entomophilic	Autochory	IS
Fabaceae	*Chamaecrista ensiformis* var. *plurifoliolata* (Hoehne) H.S. Irwin & Barneby.	2.51 ± 0.15	0.48 ± 0.03	0.32 ± 0.03	0.4 ± 0.03	0.33 ± 0.03	Entomophilic	Autochory	IS
Fabaceae	*Simarouba amara* Aubl.	2.89 ± 0.14	0.55 ± 0.03	0.47 ± 0.03	0.16 ± 0.01	0.31 ± 0.02	Melittophilic	Zoochory	IS
Fabaceae	*Tachigali* sp.	0.47 ± 0.05	0.09 ± 0.01	0.48 ± 0.03	0.19 ± 0.02	0.3 ± 0.02	Entomophilic	Anemochory	LS
Fabaceae	*Pachira glabra* Pasq.	27.31 ± 0.56	5.19 ± 0.1	0.32 ± 0.03	0.31 ± 0.03	0.29 ± 0.03	Melittophilic	Zoochory	IS
Fabaceae	*Leucaena leucocephala* (Lam.) de Wit.	0.91 ± 0.08	0.17 ± 0.02	0.45 ± 0.03	0.15 ± 0.01	0.28 ± 0.02	Entomophilic	Anemochory	PI
Malvaceae	*Senna georgica* H.S. Irwin & Barneby var. georgica	1.58 ± 0.1	0.3 ± 0.02	0.32 ± 0.03	0.25 ± 0.02	0.28 ± 0.02	Entomophilic	Autochory	PI
Sapindaceae	*Byrsonima crassifolia* (L.) Kunth.	19.21 ± 0.7	3.67 ± 0.13	0.32 ± 0.02	0.25 ± 0.02	0.26 ± 0.02	Entomophilic	Zoochory	LS
Fabaceae	*Lueheopsis duckeana* Burret.	0.7 ± 0.06	0.14 ± 0.01	0.44 ± 0.03	0.12 ± 0.01	0.25 ± 0.02	Melittophilic	Barochory	IS
Annonaceae	*Tabebuia aurea* (Silva Manso) Benth & Hook. f.ex. S. Moore.	0.23 ± 0.03	0.04 ± 0	0.31 ± 0.02	0.26 ± 0.02	0.25 ± 0.02	Melittophilic	Anemochory	LS
Malvaceae	*Cassia* sp.	0.22 ± 0.03	0.04 ± 0	0.3 ± 0.02	0.15 ± 0.02	0.24 ± 0.02	Entomophilic	Zoochory	IS
Bignoniaceae	*Pseudobombax munguba* (Mart. & Zucc.) Dugand	1 ± 0.11	0.19 ± 0.02	0.31 ± 0.03	0.15 ± 0.02	0.24 ± 0.02	Melittophilic	Anemochory	IS
Fabaceae	*Cassia fastuosa* Willd. ex.Benth.	0.22 ± 0.03	0.04 ± 0.01	0.47 ± 0.03	0.03 ± 0	0.22 ± 0.01	Entomophilic	Zoochory	IS
Malvaceae	*Tachigali myrmecophila* (Ducke) Ducke.	0.24 ± 0.03	0.04 ± 0.01	0.17 ± 0.02	0.29 ± 0.03	0.22 ± 0.02	Entomophilic	Anemochory	LS
Fabaceae	*Bauhinia* sp.	6.01 ± 0.33	1.17 ± 0.07	0.33 ± 0.03	0.1 ± 0.01	0.19 ± 0.01	Entomophilic	Autochory	IS
Fabaceae	*Mabea fistulifera* Benth.	12.94 ± 0.74	2.46 ± 0.14	0.16 ± 0.02	0.22 ± 0.03	0.19 ± 0.02	Melittophilic	Zoochory	PI
Fabaceae	*Annona mucosa* Jacq.	0.47 ± 0.04	0.09 ± 0.01	0.32 ± 0.03	0.09 ± 0.01	0.17 ± 0.01	Entomophilic	Zoochory	IS

Meliaceae	*Bagassa guianensis* Aubl.	1.17 ± 0.09	0.22 ± 0.02	0.31 ± 0.02	0.09 ± 0.01	0.16 ± 0.01	Entomophilic	Zoochory	IS
Bignoniaceae	*Euterpe oleracea* Mart.	0.22 ± 0.03	0.04 ± 0	0.16 ± 0.02	0.2 ± 0.02	0.16 ± 0.02	Entomophilic	Zoochory	IS
Fabaceae	*Machaerium froesii* Rudd.	1.9 ± 0.21	0.36 ± 0.04	0.31 ± 0.03	0.09 ± 0.01	0.16 ± 0.01	Entomophilic	Anemochory	IS
Fabaceae	*Spondias mombin* L.	3.98 ± 0.21	0.77 ± 0.04	0.31 ± 0.02	0.09 ± 0.01	0.16 ± 0.01	Entomophilic	Zoochory	PI
Fabaceae	*Sterculia* sp.	0.46 ± 0.05	0.09 ± 0.01	0.14 ± 0.02	0.12 ± 0.02	0.15 ± 0.02	Melittophilic	Zoochory	IS
Simaroubaceae	*Stryphnodendron coriaceum* Benth.	0.21 ± 0.03	0.04 ± 0.01	0.31 ± 0.02	0.01 ± 0	0.15 ± 0.01	Entomophilic	Zoochory	PI
Bixaceae	*Bowdichia nitida* Spruce ex.Benth.	1.39 ± 0.12	0.26 ± 0.02	0.16 ± 0.02	0.14 ± 0.02	0.13 ± 0.01	Entomophilic	Anemochory	LS
Fabaceae	*Derris* sp.	1.25 ± 0.11	0.23 ± 0.02	0.16 ± 0.02	0.08 ± 0.01	0.13 ± 0.01	Entomophilic	Anemochory	PI
Anacardiaceae	*Mangifera indica* L.	0.38 ± 0.05	0.07 ± 0.01	0.16 ± 0.02	0.13 ± 0.02	0.12 ± 0.01	Entomophilic	Zoochory	PI
Malvaceae	*Swietenia.macrophylla* King.	24.8 ± 0.72	4.77 ± 0.14	0.15 ± 0.02	0.12 ± 0.01	0.12 ± 0.01	Entomophilic	Anemochory	LS
Bignoniaceae	*Clitoria arborea* Benth.	5.94 ± 0.29	1.15 ± 0.06	0.13 ± 0.02	0.11 ± 0.01	0.11 ± 0.01	Entomophilic	Autochory	PI
Fabaceae	*Hymenaea courbaril* L.	0.23 ± 0.03	0.04 ± 0.01	0.16 ± 0.02	0.05 ± 0.01	0.1 ± 0.01	Melittophilic	Zoochory	CL
Fabaceae	*Hymenaea* sp.	2.21 ± 0.1	0.42 ± 0.02	0.16 ± 0.02	0.06 ± 0.01	0.1 ± 0.01	Melittophilic	Zoochory	LS
Fabaceae	*Andira* sp.	0.24 ± 0.03	0.04 ± 0.01	0.16 ± 0.02	0.07 ± 0.01	0.09 ± 0.01	Melittophilic	Zoochory	PI
Fabaceae	*Chrysophyllum prieurii* A. DC.	0.46 ± 0.05	0.09 ± 0.01	0.16 ± 0.02	0.07 ± 0.01	0.09 ± 0.01	Entomophilic	Zoochory	LS
Fabaceae	*Parkia multijuga* Benth.	2.5 ± 0.16	0.47 ± 0.03	0.16 ± 0.02	0.07 ± 0.01	0.09 ± 0.01	Entomophilic	Zoochory	LS
Fabaceae	*Anadenanthera peregrina* (L.) Speg.	0.46 ± 0.05	0.08 ± 0.01	0.15 ± 0.02	0.01 ± 0	0.08 ± 0.01	Entomophilic	Autochory	IS
Arecaceae	*Cenostigma tocantinum* Ducke.	1.66 ± 0.1	0.31 ± 0.02	0.16 ± 0.02	0.03 ± 0	0.08 ± 0.01	Entomophilic	Anemochory	IS

Fabaceae	*Copaifera* sp.	0.23 ± 0.03	0.04 ± 0	0.16 ± 0.02	0.03 ± 0	0.08 ± 0.01	Entomophilic	Zoochory	LS
Bignoniaceae	*Parkia paraensis* Ducke.	1.31 ± 0.13	0.26 ± 0.03	0.15 ± 0.02	0.01 ± 0	0.08 ± 0.01	Entomophilic	Zoochory	LS
Fabaceae	*Sapindus saponaria* L.	16.27 ± 0.52	3.08 ± 0.1	0.16 ± 0.02	0.03 ± 0	0.08 ± 0.01	Entomophilic	Zoochory	PI
Fabaceae	*Bixa orellana* L.	8.39 ± 0.37	1.59 ± 0.07	0.15 ± 0.02	0 ± 0	0.07 ± 0.01	Melittophilic	Zoochory	PI
Malpighiaceae	*Chloroleucon acacioides* (Ducke) Barneby & J.W.Grimes	0.22 ± 0.03	0.04 ± 0	0.15 ± 0.02	0 ± 0	0.07 ± 0.01	Entomophilic	Zoochory	PI
Sapotaceae	*Cordia goeldiana* Huber.	24.62 ± 0.71	4.63 ± 0.13	0.16 ± 0.02	0 ± 0	0.07 ± 0.01	Entomophilic	Anemochory	LS
Fabaceae	*Ficus malacocarpa* Standl.	4.35 ± 0.22	0.83 ± 0.04	0.15 ± 0.02	0 ± 0	0.07 ± 0.01	Entomophilic	Zoochory	IS
Fabaceae	*Ficus* sp.	1.17 ± 0.11	0.23 ± 0.02	0.16 ± 0.02	0 ± 0	0.07 ± 0.01	Entomophilic	Zoochory	IS
Malpighiaceae	*Hymenaea parvifolia* Huber.	18.33 ± 0.6	3.48 ± 0.11	0.15 ± 0.02	0.03 ± 0	0.07 ± 0.01	Melittophilic	Zoochory	LS
Lauraceae	*Inga* sp.	3.66 ± 0.15	0.7 ± 0.03	0.15 ± 0.02	0.03 ± 0	0.07 ± 0.01	Entomophilic	Zoochory	LS
Moraceae	*Ochroma pyramidale* (Cav. ex.Lam.) Urb.	0.69 ± 0.08	0.13 ± 0.01	0.15 ± 0.02	0.03 ± 0	0.07 ± 0.01	Melittophilic	Zoochory	PI
Fabaceae	*Ocotea* sp.	0.22 ± 0.03	0.04 ± 0.01	0.14 ± 0.02	0.03 ± 0	0.07 ± 0.01	Entomophilic	Zoochory	LS
Fabaceae	*Senna silvestris* (Vell.) H.S.Irwin & Barneby.	1.33 ± 0.13	0.25 ± 0.02	0.15 ± 0.02	0 ± 0	0.07 ± 0.01	Entomophilic	Autochory	IS
Fabaceae	*Balizia pedicellaris* (DC.) Barneby & J.W.Grimes	0.23 ± 0.03	0.04 ± 0	0.15 ± 0.02	0 ± 0	0.06 ± 0.01	Fanelofilia	Autochory	LS
Fabaceae	*Guazuma ulmifolia* Lam.	0.23 ± 0.03	0.04 ± 0	0.15 ± 0.02	0 ± 0	0.06 ± 0.01	Melittophilic	Zoochory	PI

Table S4. Species list at the natural regeneration sites with phytosociological values, pollination and dispersal syndromes, and successional group (PI = Pioneers species; IS = Initial secondary species; LS = Late secondary and CL = Climax species).

Family	Species	No.	AR	FR	DoR	IVI	Pollination	Dispersal	SG
Euphorbiaceae	*Croton matourensis* Aubl.	89.19 ± 0.57	57.35 ± 0.23	31.72 ± 0.13	61.37 ± 0.25	50.15 ± 0.19	Zoophilic	Barochory	PI
Solanaceae	*Solanum crinitum* Lam.	19.64 ± 0.14	12.7 ± 0.11	15.88 ± 0.1	11.94 ± 0.11	13.51 ± 0.1	Entomophilic	Zoochory	PI
hypericaceae	*Vismia guianensis* (Aubl.) Choisy	15.26 ± 0.16	9.83 ± 0.1	11.2 ± 0.08	9.65 ± 0.13	10.22 ± 0.09	Entomophilic	Zoochory	PI
Salicaceae	*Casearia javitensis* Kunth.	8.03 ± 0.12	5.17 ± 0.07	6.33 ± 0.07	5.8 ± 0.1	5.77 ± 0.07	Entomophilic	Zoochory	IS
Malpighiaceae	*Byrsonima crassifolia* (L.) Kunth.	6.22 ± 0.06	4.03 ± 0.05	7.96 ± 0.08	3.42 ± 0.04	5.14 ± 0.05	Entomophilic	Zoochory	LS
Solanaceae	*Solanum* sp.2	4.45 ± 0.06	2.88 ± 0.04	4.75 ± 0.06	1.13 ± 0.02	2.92 ± 0.04	Entomophilic	Zoochory	PI
Rutaceae	*Zanthoxylum pentandrum* (Aubl.) R.A. Howard	2.67 ± 0.03	1.73 ± 0.02	4.76 ± 0.06	1.74 ± 0.02	2.74 ± 0.04	Entomophilic	Autochory	PI
Euphorbiaceae	*Croton ascendens* Secco & N.A. Rosa	2.67 ± 0.03	1.73 ± 0.02	4.76 ± 0.06	1.46 ± 0.02	2.65 ± 0.03	Zoophilic	Autochory	PI
Annonaceae	*Guatteria poeppigiana* Mart.	1.77 ± 0.03	1.14 ± 0.02	3.16 ± 0.05	0.97 ± 0.02	1.76 ± 0.03	Entomophilic	Zoochory	PI
Cannabaceae	*Trema micrantha* (L.) Blume	1.77 ± 0.03	1.15 ± 0.02	3.15 ± 0.05	0.76 ± 0.01	1.69 ± 0.03	Entomophilic	Zoochory	PI
Euphorbiaceae	*Manihot brachyloba.* Müll. Arg.	0.88 ± 0.02	0.57 ± 0.01	1.57 ± 0.04	0.75 ± 0.02	0.96 ± 0.02	Zoophilic	Barochory	PI
Urticaceae	*Cecropia* sp.3	0.89 ± 0.02	0.58 ± 0.01	1.59 ± 0.03	0.49 ± 0.01	0.89 ± 0.02	Anemophilic	Zoochory	PI
Lecythidaceae	*Eschweilera* sp.2	0.89 ± 0.02	0.57 ± 0.01	1.58 ± 0.03	0.49 ± 0.01	0.88 ± 0.02	Melittophilic	Zoochory	LS
Urticaceae	*Cecropia concolor* Willd.	0.89 ± 0.02	0.58 ± 0.01	1.59 ± 0.03	0.03 ± 0	0.73 ± 0.02	Anemophilic	Zoochory	PI

Table S5. Species list at the assisted natural regeneration sites with phytosociological values, pollination and dispersal syndromes, and successional group (PI = Pioneers species; IS = Initial secondary species; LS = Late secondary and CL = Climax species).

Familiy	Species	No.	AR	FR	DoR	IVI	Pollination	Dispersal	SG
Fabaceae	*Anadenanthera peregrina* (L.) Speg.	19.95 ± 0.18	23.56 ± 0.2	29.87 ± 0.2	23.56 ± 0.2	25.67 ± 0.18	Entomophilic	Autochory	IS
Urticaceae	*Cecropia distachya* Huber	19.89 ± 0.33	23.8 ± 0.47	16.48 ± 0.26	23.8 ± 0.47	21.36 ± 0.39	Anemophilic	Zoochory	PI
Urticaceae	*Cecropia* sp.1	17.76 ± 0.29	20.55 ± 0.26	16.25 ± 0.14	20.55 ± 0.26	19.11 ± 0.2	Anemophilic	Zoochory	PI
Urticaceae	*Cecropia* sp.2	9.34 ± 0.31	10.32 ± 0.35	2.68 ± 0.09	10.32 ± 0.35	7.78 ± 0.26	Anemophilic	Zoochory	PI
Malvaceae	*Ceiba pentandra* (L.) Gaertn.	4.52 ± 0.13	5.4 ± 0.17	5.35 ± 0.13	5.4 ± 0.17	5.39 ± 0.15	Entomophilic	Anemochory	LS
Celastraceae	*Cheiloclinium* sp.	3.08 ± 0.06	3.57 ± 0.06	8.08 ± 0.15	3.57 ± 0.06	5.08 ± 0.09	Anemophilic	Zoochory	IS
Euphorbiaceae	*Croton matourensis* Aubl.	2.34 ± 0.06	2.65 ± 0.05	5.34 ± 0.1	2.65 ± 0.05	3.54 ± 0.07	Zoophilic	Barochory	PI
Fabaceae	*Schizolobium parahyba* var. *amazonicum* (Huber ex Ducke) Barneby	3.14 ± 0.1	3.71 ± 0.13	2.65 ± 0.09	3.71 ± 0.13	3.36 ± 0.11	Entomophilic	Zoochory	PI
Fabaceae	*Senegalia polyphylla* (DC.) Britton & Rose	2.36 ± 0.08	2.78 ± 0.1	2.65 ± 0.09	2.78 ± 0.1	2.74 ± 0.09	Entomophilic	Autochory	PI
Solanaceae	*Solanum crinitum* Lam.	0.78 ± 0.03	0.93 ± 0.03	2.65 ± 0.09	0.93 ± 0.03	1.5 ± 0.05	Entomophilic	Zoochory	PI
Solanaceae	*Solanum paniculatum* L.	0.78 ± 0.03	0.93 ± 0.03	2.65 ± 0.09	0.93 ± 0.03	1.5 ± 0.05	Entomophilic	Zoochory	PI
Cannabaceae	*Trema micrantha* (L.) Blume	0.78 ± 0.03	0.93 ± 0.03	2.65 ± 0.09	0.93 ± 0.03	1.5 ± 0.05	Entomophilic	Zoochory	PI
hypericaceae	*Vismia guianensis* (Aubl.) Choisy	0.78 ± 0.03	0.86 ± 0.03	2.68 ± 0.09	0.86 ± 0.03	1.47 ± 0.05	Entomophilic	Zoochory	PI

Table S6. Phytosociological analyses of the ecological groups in the seedling planting, natural regeneration and assisted natural regeneration sites.

	Sucessional groups	Family	Species	No.Plants.	DR%	FR%	DoR%	IVI%
Seedling planting	Pioneer	5.9 ± 0.04	15.9 ± 0.13	151.9 ± 1.43	28.9 ± 0.22	31.9 ± 0.09	29.5 ± 0.26	30.2 ± 0.15
	Initial secondary	7.3 ± 0.05	18.9 ± 0.21	117.8 ± 1.57	22.4 ± 0.26	29.7 ± 0.11	21.2 ± 0.29	24.4 ± 0.19
	Late secondary	10.8 ± 0.06	23.4 ± 0.17	248.7 ± 1.81	47.9 ± 0.3	31.9 ± 0.09	49 ± 0.33	42.9 ± 0.22
	Climax	1.1 ± 0.03	1.1 ± 0.03	5.4 ± 0.29	1 ± 0.06	6.4 ± 0.21	0.3 ± 0.02	2.6 ± 0.09
Natural regeneration	Pioneer	6.9 ± 0.01	10.7 ± 0.03	139.4 ± 0.56	90.2 ± 0.09	80 ± 0.11	90.3 ± 0.11	86.9 ± 0.09
	Initial secondary	1.9 ± 0.01	1 ± 0	7.9 ± 0.12	5.1 ± 0.08	7.9 ± 0.08	5.8 ± 0.1	6.3 ± 0.08
	Late secondary	1.9 ± 0.02	1.9 ± 0.02	7.1 ± 0.06	4.6 ± 0.05	11.9 ± 0.1	3.9 ± 0.04	6.8 ± 0.06
Assisted natural regeneration	Pioneer	5.5 ± 0.06	9 ± 0.09	81.2 ± 0.78	94.6 ± 0.16	86.6 ± 0.28	94.6 ± 0.16	92 ± 0.18
	Initial secondary	1.5 ± 0.05	1.5 ± 0.05	3.8 ± 0.13	4.5 ± 0.16	6.5 ± 0.22	4.5 ± 0.16	5.2 ± 0.18
	Late secondary	0.8 ± 0.03	0.8 ± 0.03	0.8 ± 0.03	0.8 ± 0.03	6.7 ± 0.22	0.9 ± 0.03	2.8 ± 0.09

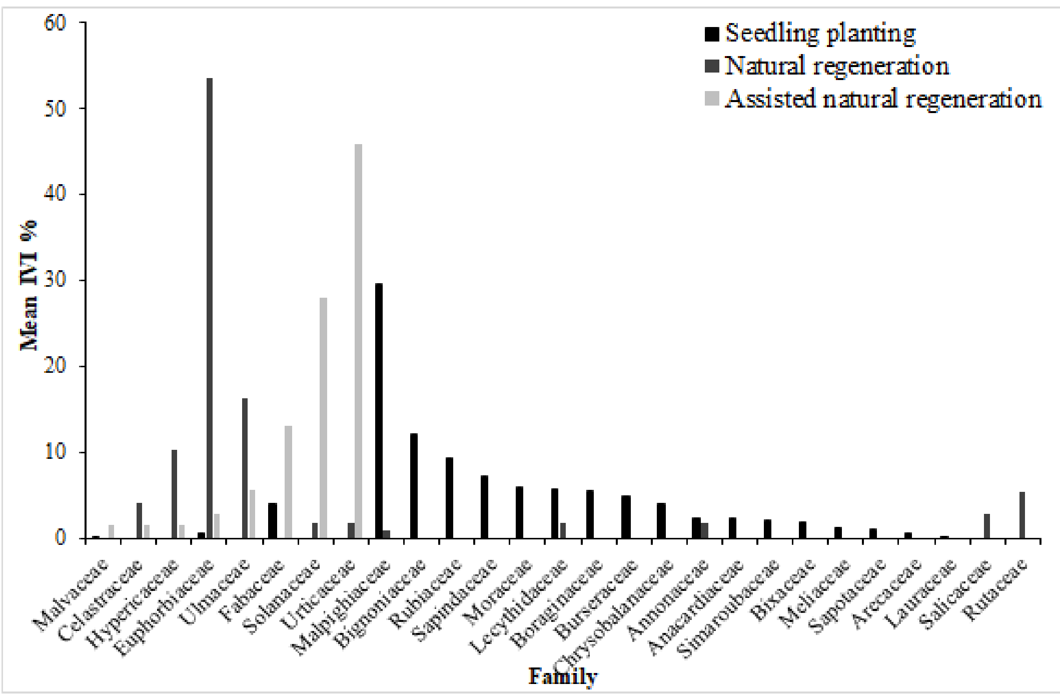

Figure S1. Mean Importance Value Indices for each botanical family found at seedling planting, natural regeneration, and assisted natural regeneration sites.

6. CONCLUSIONS

This chapter reports the major conclusions of this Thesis. Conclusion 1 is related to the starting hypothesis. Conclusions 2-3, 4, 5, and 6-7 are linked to chapters 2, 3, 4, and 5, respectively. Conclusion 8 overlaps chapters 4 and 5. Conclusion 9 summarizes the major lessons I have learnt. Finally, Conclusion 10 highlights some tips for future research of forest restoration in the Brazilian Amazon.

1. The overall results confirm the starting hypothesis that the region, regarded as the largest tropical forest and tree reserve in the world that harbors ca. 10% of the terrestrial species, has undergone severe deforestation and, concomitantly, offers outstanding opportunities for forest restoration that will enhance tree diversity and ecosystem services such as regulation of soil erosion.

2. The Brazilian Amazon has been exploited irrationally for many years mainly due to government incentives. This has resulted in a net forest loss of 788,535 km² (2% yr^{-1}) in the 1975-2018 period. The countless efforts to reduce deforestation over the last decades, which have mostly stemmed from the academia, environmental NGOs, and the Federal Government, has reduced deforestation rate, which was 9,528 km² (0.22% yr^{-1}) in the 2015-2018 period. Unfortunately, the current Bolsonaro´s Government is fomenting several activities of intensive land use that are resulting in large amounts of forest loss and degradation in the region.

3. Our systematic data collection gathered from 12 universities, five major environmental agencies, and an *ad-hoc* bibliographic survey revealed that most information on forest restoration projects is in the gray literature. The majority (229) of the 405 identified forest restoration projects used seedling planting as the main forest restoration technique, followed by agroforestry restoration (144). A large number of projects (43%) used exotic tree species. Despite the numerous restoration projects, only 152 scientific publications, 45 of which were published in international journals, were found. The region still lacks scientific studies that reinforce the choice of best practices for forest restoration, and the information currently available is not enough to quantify what has already been recovered or the potential area to be restored.

4. Multi-criteria analyses based on GIS to estimate and map the potential of vulnerability to soil erosion in the Paragominas municipality provided similar results using the RUSLE or the eco-dynamic concept of the physical and biotic environment. In spite 45% of Paragominas has already been deforested, only 3% of land exhibits a high soil erosion potential. The obtained results can assist planning land management practices, select priority areas for forest restoration and minimize operational costs.

5. The assessment of 13 qualitative and quantitative indicators for monitoring forest restoration at post-bauxite mining sites resulted in an overall higher score for natural regeneration (72) than for seedling planting (54; 102 was the highest possible score for both restoration techniques). Natural regeneration, in general, provided better outcomes for species density, erosion control and prevention of exotic species whereas seedling planting provided better outcomes for species diversity and presence of wildlife.

6. A substantial amount of local tree diversity was recovered in 3-yr-old post-mining restored sites (e.g. 119 species; noticeably, four threatened species were identified in the restored sites). Sites restored with different techniques differed significantly in tree composition. Furthermore, the restoration sites also differed in their abundance, species richness, and diversity values, which were highest at the seedling planting sites, and functional groups based on the successional status. Thus, seedling planting sites were less dominated by pioneer species compared to the natural regeneration and nucleation sites, whereas entomophilic pollination and zoochory dispersal were highly represented at the three types of restored sites.

7. Abundance and species richness were negatively correlated with distance of the restored sites to seed sources. However, whereas these values sharply declined in natural regeneration and nucleation sites at > 250 m from seed sources, they were more constant in seedling planting sites.

8. In general, the combination of different restoration strategies in post-mining sites resulted in considerable levels of recovery of local tree diversity. However, post-mining forest restoration must be carefully planned and managed and the suite of restoration techniques must be adapted to the local context with a well-defined objective to achieve optimal results.

9. I have learnt that (1) the overall good performance of the restoration techniques assessed in this Thesis is in part related to the collaboration between a private mining company and academic groups; (2) economic activities in the Brazilian Amazon are far from being sustainable: and (3) restoration initiatives, whether by legal compliance or not, are critical to maintain and preserve forest ecological integrity and human well-being.

10. Future research. There is still much research to be carried out for coming up with the best restoration practices of deforested areas in the Brazilian Amazon. I suggest considering the following relevant issues: (1) consistent assessments of historical forest loss and degradation, (2) transparency in the results of restoration projects and trials, (3) highly targeted monitoring of outcomes following contrasting restoration techniques based on integrated surveys of flora and fauna, (4) identification of priority areas for forest restoration in rural properties, (5) feasibility of establishing ecological corridors, and (6) thorough evaluation by the public administration of the restoration activity based upon fine inspection and monitoring systems. In my opinion, the biggest obstacles for forest recovery in the region are lack of: (*i*) motivation of those stakeholders responsible for forest restoration in “their” deforested areas; (*ii*) assessment of the ecological, social, political, institutional and market characteristics of the target areas; (*iii*) technical know-how and (*iv*) financial resources to implement restoration projects.

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CURRÍCULUM VITAE OF THE AUTHOR

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CURRICULUM

Denis Conrado da Cruz

Academic background

- **2015-2020. Ph.D. in Ecology, Conservation and Ecosystem Restoration.** University of Alcalá (UAH), Alcalá de Henares, Spain.

Fellowship Program: National Council for Scientific and Technological Development (CNPq, Brazil).

- **2012-2014. MSc. in Geographical Information Technology.** University of Alcalá (UAH), Alcalá de Henares, Spain.
- **2006-2010. Forest engineer degree.** Federal Rural University of Amazonia (UFRA), Belém, Brazil.
- **2006-2007. Computer Technician.** State Technical School Magalhães Barata (ETEMB), Belém, Brazil.

Professional experience

Articulation analyst

- **2014-2015.** Brazilian Institute of Municipal Administration (IBAM, Portuguese: Instituo de Administração Municipal), Rio de Janeiro, Brazil.

-Supporting the strengthening of environmental management in the municipalities of the Amazon biome in the Environmental Management Qualification Program in Brazilian Amazon (PQGA, Portuguese: Programa de Qualificação da Gestão Ambiental), Amazon Biome, Brazil.

Assistant researcher

- **2009-2014.** Institute for Man and the Environment of the Amazon Region (IMAZON, Portuguese: Instituto do Homem e Meio Ambiente da Amazônia), Belém, Brazil.

- Researcher in the geoprocessing laboratory of the Brazilian Amazon monitoring program.

Scholarship

- **2009**. Federal Rural University of Amazonia (UFRA), Belém, Brazil.

-Occupation: Digital inclusion of adolescents and youth in the municipality of Igarapé-Açu, Brazil.

- **2008**. Federal Rural University of Amazonia (UFRA), Belém, Brazil.

-Occupation: Botanical research.

- **2008**. Tramontina Company, Belém, Brazil.

-Occupation: Tree species composition evaluation.

- **2007-2008**. Novos Curupiras NGO, Ananindeua, Brazil.

-Occupation: Management and conservation of marine fishery resources

- **2007**. State Technical School Magalhães Barata (ETEMB), Belém, Brazil.

-Occupation: IT Technician.

Teaching activities

Doctoral Program - University of Alcalá (UAH)

- **2nd Semester/2017**. Basic ecology discipline (Natural sciences course).
- **2nd Semester/2017**. Natural Resource management and conservation discipline (Natural sciences course).

Federal University of Pará (UFPA)

- **4th Semester/2017**. Rural evaluation and expertise discipline (Agronomy course).
- **2nd Semester/2016**. Teaching practice discipline (Natural sciences course).

Participation in research projects

- **2015-2018**. Project: Biodiversity, propagation of plant species and restoration of degraded areas from mining bauxite in the southeast region of Pará, Paragominas, Brazil.

- Main goal: Evaluate the attributes of the soil, biodiversity and plant propagation to develop a model of forest recovery for mined landscape environments, concerning ecological and economic efficiency.

- **2009**. Project: Digital inclusion of adolescents and youth in the municipality of Igarapé-Açu, Brazil.

- Main goal: Teaching needy young people the use of digital tools in Igarapé-Açu municipality.

- **2008-2014**. Project: Vale Florestar, Don Eliseu, Brazil.

- Main goal: Monitoring in permanent plots in recovery areas.

- **2008**. Project: Vale Florestar, Don Eliseu, Brazil.

- Main goal: Herbário Felisberto Camargo Informatization.

Doctoral program activities - Course (UAH)

- **2017**. Factorial designs and analysis of experiments (**40hs**). National Museum of Natural Sciences. CSIC-MNCN, Madrid, Spain
- **2016**. Advances and Quantitative Methods in Biogeography and Ecology I and II. (**48hs**). University of Alcalá, UAH, Alcalá de Henares, Spain.

Doctoral program activities - Seminar (UAH)

- **2016**. Transfer of knowledge (**10 hs**).
- **2016**. How to write a great research paper (**20 hs**).
- **2016**. Responsible in research: on authorship, plagiarism (**6 hs**).
- **2016**. Written presentation of research papers (**12 hs**).
- **2016**. Oral presentation of research papers in Spanish (**20 hs**).
- **2016**. The limits of the planet. Environmentalism and human right (**24 hs**).

Participation in others courses/ Seminar

- **2016**. Environmental Expertise (**Course; 20 hs**). Federal Rural University of Amazonia (UFRA), Belem, Brazil.
- **2015**. Career day for scientists and engineers in early stage (**Course; 8 hs**), University of Rey Juan Carlos (URJC), Móstoles, Spain.
- **2013**. Augment forest monitoring capacity in the Brazilian Amazon through radar (**Course; 120 hs**). Wageningen University (WUR), Wageningen, Nederland.
- **2011**. Fragmentation of Amazonian landscape. (**Course; 100 hs**). National Research Institute of the Amazon (INPA, Portuguese: Instituto Nacional de Pesquisa Ambiental), Manaus, Brazil.

+ (6) Courses; + (5) Seminars

Areas of expertise

- Forest resources and forest engineering; (2) Remote sensing; (3) Recovery of degraded areas; (4) Brazilian Amazon restoration; (5) Nature conservation; (6) Forest handling (7) Ecology; (8) Forest techniques and operations; (9) Environmental management and (10) Technology and use of forest products.

Languages

- English – B2
- Español – C1
- Portuguese – Native

Bibliographic Production

Scientific publication

- **da Cruz, D. C.,** Benayas, J. M. R., Ferreira, G. C., Santos, S. R., & Schwartz, G. (2020). An overview of forest loss and restoration in the Brazilian Amazon. *New Forests*, 1-16. https://doi.org/10.1007/s11056-020-09777-3.
- **da Cruz, D. C.**, Benayas, J. M. R., Ferreira, G. C., & Ribeiro, S. S. (2020). Tree Communities in Three-Year-Old Post-Mining Sites Under Different Forest Restoration Techniques in the Brazilian Amazon. *Forests*, *11*(5), 527. https://doi.org/10.3390/f11050527.
- **da Cruz, D. C.,** Benayas, J. M. R., Ferreira, G. C., Monteiro, A. L., & Schwartz, G. (2019). Evaluation of soil erosion process and conservation practices in the Paragominas-pa municipality (Brazil). *Geographia Technica, 14*(1). https://doi.org/10.21163/GT_2019.141.02.
- Ribeiro, S. S., Oliveira, F. D. A., Ferreira, G. C., Santos, D. E., & **Cruz, D. C.** (2019). Forest restoration evaluation through indicators in areas of bauxite mining. *Floresta e Ambiente, 26*(3). https://doi.org/10.1590/2179-8087.081217.

Books

- Veríssimo, A., Rolla, A., Vedoveto, M., Furtado, S de Melo., Maior, A. P. C. S., Monteiro, A., Brito, B.; Souza, C., Augusto, C. C., Cardoso, D; **da Cruz, D. C.**, Araujo, E.; Ricardo, F., Ribeiro, J., Lima, L. M., Ribeiro, M. B., Mesquita, M., Barreto, P. G., Salomao, R.. *Áreas Protegidas na Amazônia Brasileira: Avanços e Desafios. 1. ed. Liana John - projeto gráfico/ editoração Vera Feitosa/ISA*, 2011. 87p.

http://www.bibliotecadigital.abong.org.br/bitstream/handle/11465/1212/10372.pdf?sequence=1.

Scientific conference/congress

- Balieiro, M. L., **da Cruz, D. C.**., Tavares, F. B., Silva, S. D., & Cordeiro, Y. E. M. (2018). Diagnóstico socioambiental na comunidade Costa de Santana–zona ribeirinha de Mocajuba-PA, sobre a implantação da Hidroelétrica de Tucuruí. *Cadernos de Agroecologia, 13*(1).

http://cadernos.aba-agroecologia.org.br/index.php/cadernos/article/view/856.

- **da Cruz, D. C.,** Monteiro, A., Aguado, I. (2016). Identificación y Cartografía de la Extracción maderera en el estado de Pará-Brasil a partir del índice NDFI (Índice Normalizado de Diferencia de Fracción). In: *Terceras jornadas ibéricas de ecología del paisaje, Cárceres/España. Herramientas para la intervención en el paisaje.*

- Monteiro, A. L. S., **da Cruz, D. C.**, Cardoso, D. R. S., & Souza, J. (2013). Monitoramento remoto de concessões florestais na Amazônia-Flona do Jamari, Rondônia. *Simpósio Brasileiro de Sensoriamento Remoto, XVI.*

https://imazon.org.br/PDFimazon/Portugues/congressos%20e%20anais/p0205.pdf.

- Monteiro, A. L. S., de Souza Jr, C. M., **da Cruz, D. C**., & Cardoso, D. R. (2011). Avaliação de Planos de Manejo Florestal na Amazônia através de imagens de satélites Landsat. *An do XV Simpósio, 5615-5623.*

http://marte.sid.inpe.br/col/dpi.inpe.br/marte/2011/06.27.12.04/doc/p1117.pdf.

- Campos, J. R. P., Ferreira, G. C., **da Cruz, D. C.**, M. F. S. Damasceno. (2010). Levantamento florístico e fitossociológico em áreas de várzea submetidas ao manejo de açaí (Euterpe oleracea Mart.: Arecaceae) na comunidade de Sirituba/Abaetetuba/Pará. In: *61º Congresso Nacional de Botânica/Manaus.*

- **da Cruz, D. C.,** Silva, V. C. da C., Meireles, C. (2010). Avaliação do processo de produção dos brinquedos de miriti (Mauritia flesuosa Mart.), oriundos do município de Abaetetuba/Pará. In: VIII Congreso Latinoamericano de Sociologia Rural. *Porto de Galinhas. América Latina: realineamientos políticos y proyectos en disputa.*

- Melo Junior, J. G., **da Cruz, D. C.,** Silva, V. C. da C. (2010). As experiências de produção agroecológica em Assentamentos de Reforma Agrária no Estado do Pará, uma identidade da agricultura camponesa impulsionada pelos Movimentos Sociais. In: *VIII Congreso Latinoamericano de sociologia rural, Porto de Galinhas. América Latina: realineamientos políticos y proyectos en disputa.*

- Pereira, B. W. De F, **da Cruz, D. C.**, Maciel, M. de N. (2010). Inclusão digital de jovens e Adultos na Universidade federal Rural da Amazônia. Programa Ver-o-Sol. In: *I Colóquio de Engenharia para o Desenvolvimento Sustentável na Amazônia, Belém/Pará., Belém.*
- **da Cruz, D. C.** (2010). Revisão bibliográfica da doença mal das folhas em Hevea brasiliensis (Wild, ex Adr. de Juss.) Müll. Arg. In: I Colóquio de Engenharia para o Desenvolvimento Sustentável na Amazônia. Belém/Pará. Belém. *I Colóquio de Engenharia para o Desenvolvimento Sustentável na Amazônia.*
- **da Cruz, D. C.**, I. P. Gomes, Silva, V. C. da C, Brito, V. L. (2010). Análise fitossociologica de uma florestal secundária, localizada nas proximidades do centro de pesquisa Biofauna da Universidade Federal Rural da Amazônia. In: *I Colóquio de Engenharia para o Desenvolvimento Sustentável na Amazônia. Belém/Pará.*
- **da Cruz, D. C.,** I.P.Gomes, Cascae, J. B., Almeida, M. G., Silva, V. C. da C. (2010). Tratamentos culturais e teste de progênie em cacao (Theobroma cacao L.) realizado em casa de vegetação no município de Belem/Pará. In: *Anais do SBPC. Sociedade Brasileira para o Progresso da Ciência, Rio Grande do Norte.*
- **da Cruz, D. C.,** Ferreira, G., Cordeiro, I., Mourão Junior, M., & Damasceno, M. (2009). Comportamento de espécies florestais em uma capoeira de 17 anos, na fazenda Tramontina-Aurora do Pará-PA. In Embrapa Amazônia Oriental-Artigo em anais de congresso (ALICE). In: *Congresso de ecologia do brasil, 9.; congresso latino-americano de ecologia, 3., 2009, São Lourenço. Ecologia e o futuro da biosfera.[São Paulo]: SEB.*

https://www.alice.cnptia.embrapa.br/bitstream/doc/660600/1/1803.pdf.

- **da Cruz, D. C.,** Ferreira, G. C, I. M. C. C. Cordeiro, M. Mourão, M. F S Damasceno. (2009). Comportamento de espécies florestais em uma capoeira de 17 anos, na fazenda Tramontina. Aurora do Pará-PA. In: *Congresso de Ecologia, São Lourenço. Anais do Congresso de Ecologia em São Lourenço.*
- **da Cruz, D. C.,** J.R.P. Campos, Ferreira, G. C, L.L. Cruz, M. F. S, Damasceno, I. P ., Gomes. (2009). Levantamento florístico e fitossociológico em áreas de várzea submetidas ao manejo de açaí na comunidade de Arapapuzinho, Abaetetuba, Pará. In: *Anais do Congresso de Ecologia em São Lourenço, São Lourenço.*

Techinical production

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2010). Transparency in Forest Management 2008 to 2009 in the State of Pará. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-estado-do-para-2008-e-2009/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2012). Transparency in Forest Management 2010 to 2011 in the State of Pará. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/2285-2/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2013). Transparency in Forest Management 2011 to 2012 in the State of Pará. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-estado-do-para-2011-2012/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2011). Transparency in Forest Management 2009 to 2010 in the State of Mato Grosso. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-do-estado-do-mato-grosso-agosto-de-2009-a-julho-de-2010/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2011). Transparency in Forest Management 2009 to 2010 in the State of Pará. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-estado-do-para-2009-e-2010/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2011). Transparency in Forest Management 2006 to 2009 in the State of Mato Grosso. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-estado-do-mato-grosso-2006-a-2009/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2012). Transparency in Forest Management 2010 to 2011 in the State of Mato Grosso. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-do-mato-grosso-2010-2011/.

- Monteiro, A., Cardoso, D., **da Cruz, D. C.,** Verissimo, A., & Souza Jr, C. (2014). Transparency in Forest Management 2011 to 2012 in the State of Mato Grosso. Imazon, Belém, Brazil.

https://imazon.org.br/publicacoes/boletim-transparencia-manejo-florestal-do-mato-grosso-2011-2012/.

Articles in preparation

- **da Cruz, D. C.,** Ferreira, G. C., Monteiro, A., Santos, S. R., & Schwartz, G. Priority areas for restoration in permanent preservation areas of rural properties in the Brazilian Amazon. *Land Use Police.*

  Current status: Under Review

Citation

- Studies cited until 02/06/2020, updated in Academic Goggle:

Source: Academic google: https://scholar.google.es/citations?hl=es&user=s8EnYT4AAAAJ.

Reviewing experience

- **2020**. Journal of Scientific Research and Reports (1).

Course taught

- **2015**. Course on Introduction to Geotechnologies.

Academic advisories

- **2016**. Advancing deforestation in Oeiras do Pará-PA, Amazon municipality, 2000 to 2014.

-Final course assignment in Natural Science - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Heminacés Rodrigues Pimentel and Rosemir Balieiro Barbosa

- **2016**. School Feeding: Acquisition, distribution and food quality offered to students in municipal schools in Oeiras do Pará.

-Final course assignment in Natural Science - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Keverson Oliveira Pinto.

- **2016**. How environmental education has been worked in Oeiras do Pará municipality? A case of study at School Raimundo Arcanjo da Costa.

-Final course assignment in Natural Science - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Afonso de Aragão Neto and João Luis Santana Coelho

- **2016**. Literary review of the use of educational technologies in science teaching.

-Final course assignment in Natural Science - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Tiago de Oliveira Nogueira

- **2016**. Malaria epidemic in Oeiras do Pará municipality in the year 2010-2014. Causes and combat measures.

-Final course assignment in Natural Science - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Jorge Antônio Morais da Costa.

- **2016**. Contributions of PIBID in initial teacher training of fellows from the natural science subproject.

-Final course assignment in Natural Science - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Rosiney Nogueira Cardoso.

- **2016**. evaluation of Rural properties impacted by the implementation of the Tucuruí hydroelectric plant, located in the Costa da Santana community, on the riverside Mocajuba-PA municipality.

-Final course assignment in Agronomy - Federal University of Pará (UFPA).

-Advisor: Denis Conrado da Cruz; Student: Marciclei Lopes Baliero.

Presentations in events

- **da Cruz, D. C.,** Monteiro, A., Aguado, I. (2016). Identificación y Cartografía de la Extracción maderera en el estado de Pará-Brasil a partir del índice NDFI (Índice Normalizado de Diferencia de Fracción). Careces, Spain.
- **da Cruz, D. C.,** (2014). The tools to guarantee the legal origin of the wood. Belém, Brazil.
- **da Cruz, D. C.,** . I. P. Gomes, Brito, V. L., Silva, V. C. C. (2010). Análise fitossociologica de uma florestal secundária, localizada nas proximidades do centro de pesquisa Biofauna da Universidade Federal Rural da Amazônia. Belém, Brasil.
- **da Cruz, D. C.**, I. P. Gomes, Silva, V. C. da C . (2010). Tratamentos culturais e teste de progênie em cacao (Theobroma cacao L.) realizado em casa de vegetação no município de Belem, Brasil.
- **da Cruz, D. C.,** Ferreira, G. C., I. M. C. C. Cordeiro., M. Mourão. (2009). Comportamento de espécies florestais em uma capoeira de 17 anos, na fazenda Tramontina. Aurora do Pará, Brasil.

Congress

- **2017**. VII World Conference on Ecological Restoration. Foz do Iguassu, Brazil.
- **2017**. V Congreso Iberoamericano y del Caribe de Restauración Ecológica. Foz do Iguassu, Brazil.
- **2017**. I Brazilian Conference on Ecological Restoration. Foz do Iguassu, Brazil.
- **2016**. II Amazonian Congress on Environment and Renewable Energies. Belém, Brasil.
- **2016**. Congreso de Ecología de Paisaje. Cárceres, Spain.
- **2011**. XV Brazilian Remote Sensing Symposium. Curitiba, Brasil.
- **2009**. IX Congress of Ecology of Brazil. São Lourenço, Brasil
- **2009**. I Engineering Colloquium for Sustainable Development in Amazon. Belém, Brasil.
- **2009**. World Social Forum Amazon. Belém. Brasil
- **2007**. II Encuentro Internacional de Reservas de la Biosfera en la Amazonía. Belém, Brasil.
- **2007**. V AMAZONIADA (In defense of the Amazon). Belém, Brasil

Volunteering

- **2016-2018**. Volunteering at Amnesty International, Alcalá de Henares, Spain.

Event production

- **2010**. Round table entitled conservation and forest concession units in Pará state. Quintas do Saber Project Socioenvironmental at UFRA, Belém, Brazil.
- **2010**. Round table entitled global climate change and the reflections in the Amazon. Belém, Brazil.
- **2010**. Round table entitled another economy is possible: The use of biodiversity by traditional communities, Belém, Brazil.
- **2010**. Conservation and forest concession units in Pará - Quinta do saber Environmental Socioenvironmental Project at UFRA, Belém, Brazil.
- **2009**. 7º UFRA's Scientific Initiation Seminar, 13th EMBRAPA's Scientific Initiation Seminar and UFRA's 1st Research Seminar, Belém, Brazil.