MINISTÉRIO DA EDUCAÇÃO
UNIVERSIDADE FEDERAL RURAL DA AMAZÔNIA

SABRINA SANTOS RIBEIRO

AVALIAÇÃO DO POTENCIAL DA RESTAURAÇÃO FLORESTAL NA AMAZÔNIA ORIENTAL: ESTUDOS APLICADOS AO NORDESTE PARAENSE.

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Tese apresentada à Universidade Federal Rural da Amazônia do curso de Doutorado do Programa de Pós-Graduação em Ciências Florestais.

Orientador: Dr. Gustavo Schwartz
Co-orientador: Dr. Denis Conrado da Cruz
Dra. Gracialda Costa Ferreira

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Defesa de tese apresentada à Universidade Federal Rural da Amazônia, como parte das exigências do curso de Doutorado em Ciências Florestais para obtenção do título de Doutor.

BANCA EXAMINADORA

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Essa tese tem um sentido muito especial:

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Marthin Luther King

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RESUMO

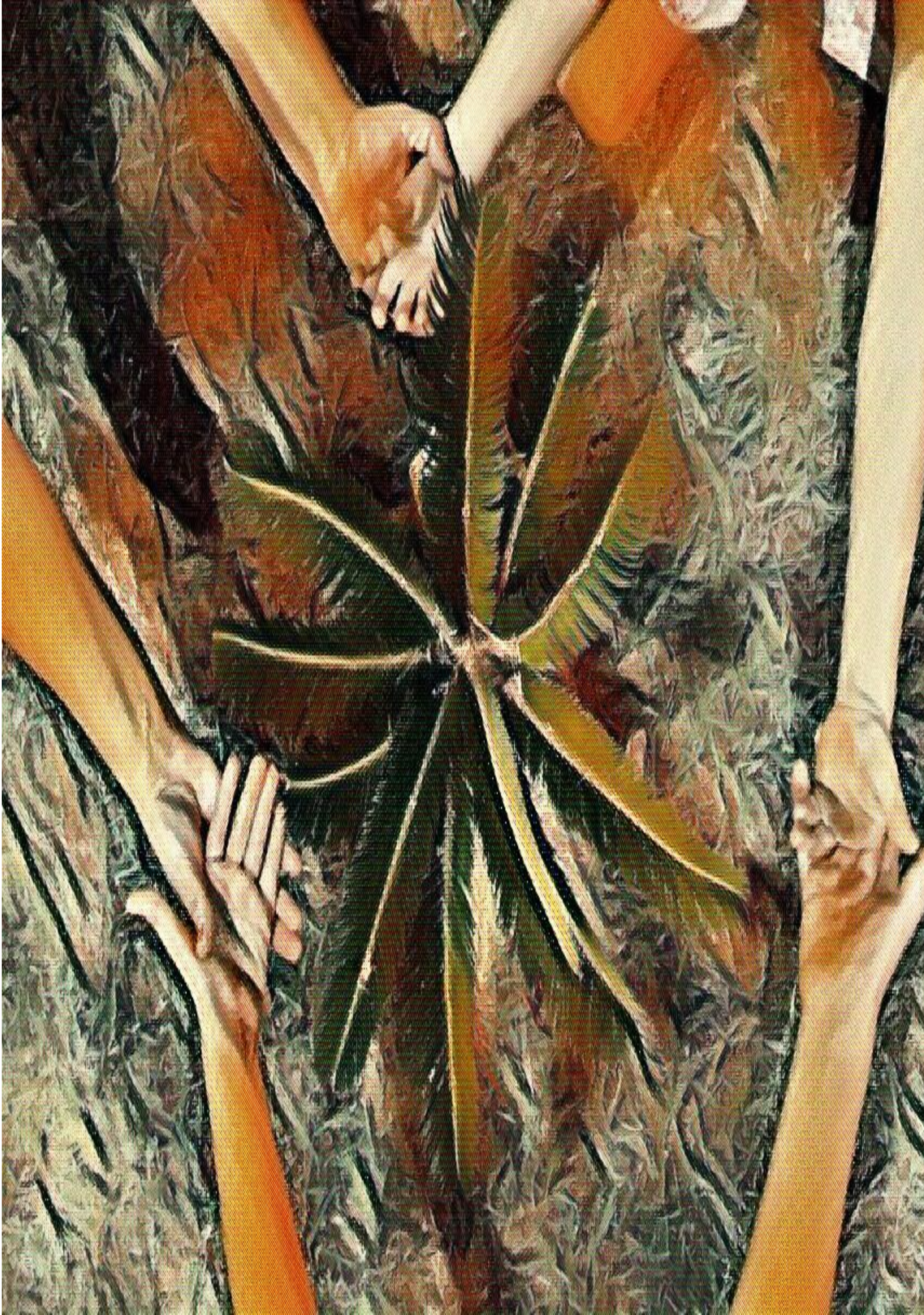
O Brasil possui uma meta de restaurar 350 milhões de hectares até 2030, com métodos e técnicas que proporcionem melhores benefícios ecossistêmicos aliados ao processo de custo-eficiência e, por outro lado, detém em sua economia, atividades que requerem a supressão de extensas áreas, tais como pecuária, agricultura e mineração. Considerando os impactos gerados pela supressão da vegetação e a busca por alternativas eficientes de restauração desses ambientes, a presente tese teve por objetivo avaliar o potencial de restauração florestal na Amazônia brasileira, com enfoque na região do nordeste paraense, e propor métodos de restauração eficientes à realidade pós-mineração. Está Tese de Doutorado está dividida em seis capítulos: (1) **Introdução Geral**, abordando os principais aspectos presente na Tese; (2), (3) e (4) **Capítulos de Pesquisa**, apresentados aqui em forma de publicação cientificas, enviados a revistas internacionais de alto impacto; (5) **Discussão Geral**, onde abordamos os aspectos de conexão entre os capítulos de pesquisa; e (6), **Capítulo de Conclusões**. No primeiro capítulo foi abordado a avaliação de áreas prioritárias para a restauração do município de Paragominas, no qual foi avaliado o processo histórico de degradação em propriedades rurais e proposto restaurar Àreas de Preservação Permanentes (APP) degradadas, bem como a possibilidade de implementação de corredores ecológicos, e assim fomentar alternativas de retorno da biodiversidade. Nesse capítulo identificamos 3.472,96 km2 de propriedades rurais com APPs degradadas que devem ser recuperadas. No segundo capítulo, foi estudado o processo de sucessão florestal de uma área minerada por caulim pertencente a empresa Imerys, no município Ipixuna, caracterizada pela grande desestruturação topográfica, no qual se buscou avaliar a eficiência de um método de restauração ainda pouco difundido, com abertura de trincheiras, para avaliação da composição florística de seis espécies florestais e estoque de serapilheira após 18 meses de implantação. Os resultados demonstrados são promissores, onde a abertura de trincheiras com adição de adubação orgânica somada de adubação química nas covas foi positivo no desenvolvimento dos indivíduos plantados, apesar de haver a necessidade de se avaliar o custo-eficiência para demonstrar que a técnica pode ser utilizada em áreas extensas de mineração. No terceiro capítulo, para a mesma área em processo de sucessão pós mineração de caulim o objetivo foi avaliar a eficiência dos atributos químicos do minesoil, em função de diferentes técnicas de adubação. Os resultados demonstraram que, apesar do pouco tempo, a metodologia aplicada favoreceu ao solo boas propriedades físicas e químicas, rápido crescimento dos indivíduos plantados e ambiente favorável à regeneração natural. Dessa forma, os resultados obtidos nesses estudos podem ser replicados a outros municípios para propor políticas públicas na busca pela diminuição da degradação ambiental, assim como propor alternativas viáveis para os empreendimentos minerários que requerem de forma eficiente, restaurar os ambientes minerados.

Palavra-Chave: Mineração, Sustentabilidade, Restauração florestal, Solos, minesoil, trincheiras.

ABSTRACT

Brazil has a goal of restoring 350 million hectares by 2030, with methods and techniques that provide better ecosystem benefits coupled with the cost-efficiency process and, on the other hand, holds in its economy, activities that require the suppression of extensive areas, such as livestock, agriculture, and mining. Considering the impacts generated by suppression of vegetation and the search for efficient alternatives for the restoration of these environments, the present thesis aimed to evaluate the potential of forest restoration in the Brazilian Amazon, focusing on the northeast region of Pará, and to propose efficient restoration methods to post-mining reality. This Doctoral Thesis is divided into six chapters: (1) **General Introduction**, covering the main aspects present in the Thesis; (2), (3) and (4) **Research Chapters**, presented here in the form of scientific publications, sent to high impact international journals; (5) **General Discussion**, where we address the aspects of connection between the research chapters; and (6), **Conclusions Chapter**. In the first chapter, the evaluation of priority areas for restoration in the municipality of Paragominas was addressed, and the historical process of degradation in rural properties was evaluated and it was proposed to restore degraded Permanent Preservation Areas (PPA), as well as the possibility of implementing ecological corridors, and thus foster alternatives for the return of biodiversity. In this chapter, we identified 3,472.96 km^2 of rural properties with degraded PPA’s that must be recovered. In the second chapter, the process of forest succession of an area mined by kaolin belonging to the company Imerys, in Ipixuna municipality, was studied, characterized by the great topographical disruption, in which it sought to evaluate the efficiency of a restoration method that is still not very widespread, of trenches, to evaluate the floristic composition of six forest species and litter stock after 18 months of implantation. The results demonstrated are promising, where the opening of trenches with the addition of organic fertilizer plus chemical fertilizer in the pits was positive in the development of the planted individuals, although there is a must to evaluate the cost-efficiency to demonstrate that the technique can be used extensive mining areas. In the third chapter, for the same area in succession process after kaolin mining, the objective was to evaluate the efficiency of the chemical attributes of minesoil, according to different fertilization techniques. The results showed that, despite the short time, the applied methodology favored the soil with good physical and chemical properties, rapid growth of planted individuals and a favorable environment for natural regeneration. In this way, the results obtained in these studies can be replicated to other municipalities to propose public policies in the search for the reduction of environmental degradation, as well as to propose viable alternatives for mining enterprises that require efficiently, to restore the mined environments.

Keywords: Mining, Sustainability, Forest restoration, Soils, minesoil, trenches.



1. CAPÍTULO I: CONTEXTUALIZAÇÃO

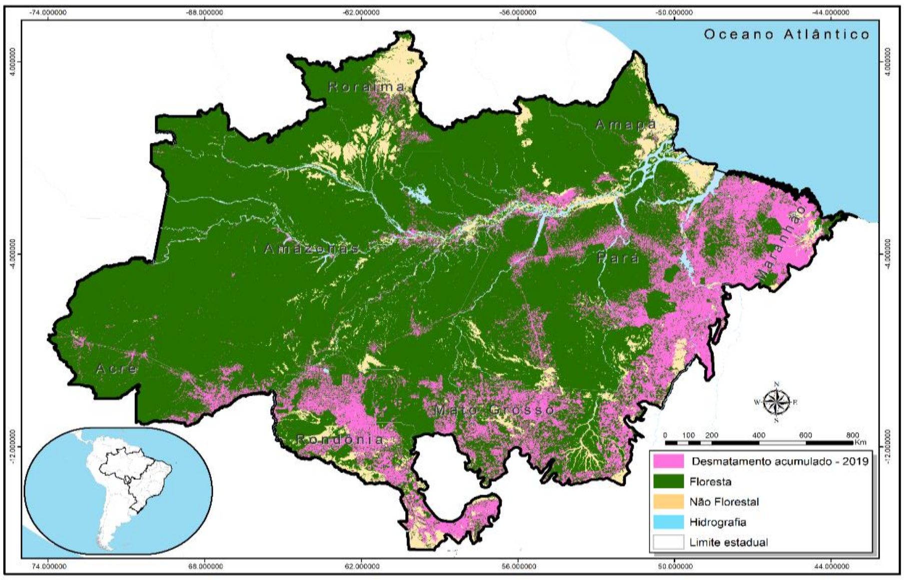
1.1. Desmatamento na Amazônia

O maior remanescente florestal tropical do mundo está presente na Amazônia Brasileira (5,2 milhões de km²; 61% do território do país), representado por nove estados brasileiros (IBGE, 2015). A região possui um número estimado em milhões de espécies, com uma das maiores reservas de água doce do planeta (MAY, 2010). Entretanto, todo esse potencial vivo, está sendo ameaçado pela ação antrópica, que ao longo dos anos deixou uma Amazônia bastante alterada, principalmente pela conversão de grandes áreas em pastagens e agriculturas, abertura de estradas, incêndios e extração de madeira e minério (SOLAR et al., 2016).

O Brasil possui os maiores índices de desmatamento e emissões entre os países pertencentes a Amazônia (85,4%; 79,9% respectivamente), sendo o estado do Pará o que mais desmata dentro do bioma, considerando o quantitativo de todos os demais países amazônicos, ainda liderando o menor percentual de restauração (SMITH et al., 2021).

O processo de desmatamento em grande escala na Amazônia brasileira iniciou na década de 1970 pelos incentivos governamentais na tentativa de impulsionar o desenvolvimento econômico da região (REYDON; FERNANDES; TELLES, 2015). De 1985 a 2018, 65 milhões de hectares de florestas e savanas na Amazônia brasileira foram convertidas em pastagens e terras agrícolas (STABILE et al., 2020). Como consequência, vieram vários impactos relacionados às alterações da paisagem, políticas governamentais ineficientes, mineração ilegal e incêndios, que resultaram em altas taxas de desmatamento e, hoje, a Amazônia brasileira conta com aproximadamente 20% a menos de sua floresta original (DA CRUZ et al., 2020; **Figura 1**).

Figura 1. Desmatamento acumulado na Amazônia Brasileira



Fonte: Elaboração própria. Bases de dados do IBGE – Instituto Brasileiro de Geografia e Estatística (https://www.ibge.gov.br/geociencias/informacoes-ambientais/15842-biomas.html), e INPE – Instituto Nacional de Pesquisas Espaciais (http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes).

Ao longo dos anos, medidas e ações foram tomadas para reduzir o desmatamento na região Amazônica, dentre elas a criação dos sistemas DEGRAD (mapeamento anual de áreas de floresta degradada na Amazônia), PRODES (monitoramento por satélite do desmatamento por corte raso na Amazônia Legal) e o DETER (levantamento de alertas de evidências de alteração da cobertura florestal na Amazônia), que formam um conjunto de sistemas para monitoramento e acompanhamento do estado da floresta, criados a partir do Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal – PPCDAm, em 2004 (INPE, 2020). Com esse plano, foram obtidos resultados favoráveis na redução do desmatamento, por meio políticas de controle e incentivos econômicos (LAPOLA et al., 2014). Entretanto, essas políticas dependem da intervenção direta do Estado, consequentemente se manter por longo prazo não é uma tarefa fácil, o que evidencia a ausência de governança nestas áreas (REYDON; FERNANDES; TELLES, 2019).

Apesar de todas as medidas adotadas ao longo dos anos, tanto por organizações nacionais como internacionais no combate às diversas irregularidades na Amazônia Brasileira, os índices de degradação e desmatamento vêm aumentando (ESCOBAR, 2019). O compromisso assumido pelo Brasil em zerar as taxas de desmatamento na região parece ser uma tarefa impossível de cumprir considerando as atuais políticas do governo federal (ARTAXO, 2019), que se refletem no aumento das taxas de desmatamento no país, sobretudo na Amazônia. No período de agosto de 2018 a julho de 2019, houve um aumento de 30% (9.762 km^2) nas taxas de desmatamento na Amazônia em relação ao mesmo período do ano anterior (INPE, 2020). Toda essa alteração na paisagem gera consideráveis mudanças nos meios bióticos e abióticos do ecossistema Amazônico (AMARAL E SILVA et al., 2020; COPERTINO et al., 2019).

Compromissos internacionais, nacionais e regionais para a restauração das florestas no mundo propõem a meta de restaurar 350 milhões de hectares até 2030 (GUERRA et al., 2020). Nesse contexto, o Brasil possui uma meta estabelecida pelo Plano Nacional de Recuperação da Vegetação Nativa de 12 milhões de hectares até 2030 (MMA, 2017). Essa meta foi estabelecida com o objetivo de reduzir em pelo menos 37% as emissões de gases do efeito estufa até 2025. A expectativa é que a redução nestas emissões deverá gerar US$ 170 bilhões/ano em benefícios relacionados à proteção de bacias hidrográficas, melhoria de técnicas relacionadas ao manejo de produtos florestais e sequestro de 1,7 giga toneladas de dióxido de carbono anualmente (CROUZEILLES et al., 2019).

No caso do Pará, segundo Decreto nª 941/ 2020 que institui o Plano Estadual Amazônia Agora (PEAA), a meta do estado é a redução das emissões brutas de Gases de Efeito Estufa (GEE) em, no mínimo, 37% da média da linha de base, corroborando a meta estabelecida para o Brasil, além da meta de regeneração da vegetação em 5,65 milhões de hectares até o ano de 2030.

1.2. Município: do desmatador ao modelo de sustentabilidade

O município de Paragominas, no estado do Pará, possui uma extensão territorial de 19.342 km² e teve sua ocupação e desenvolvimento fomentados pela construção da rodovia Belém- Brasília em 1965, que fazia parte de um Plano de Integração Nacional (PIN) que objetivava a integração da Amazônia com o restante do território nacional, por meio da abertura de estradas (OLIVEIRA et al., 2012). Nesta época, o incentivo do governo federal era para que colonos de novos municípios da região amazônica desmatassem e ocupassem terras públicas, com a promessa de receber títulos de terras se a terra fosse considerada produtiva (BRITO, 2019). Um dos incentivos ao desenvolvimento da região foi a criação de Polos Agropecuários e Agrominerais da Amazônia (Polamazônia), em 1974, sob pressão da Associação dos Empresários da Amazônia (AEA) que fomentaram a ocupação de grandes latifundiários para a exploração florestal e mineral e implantação de pecuária (OLIVEIRA et al., 2012). Como consequência disso, as atividades de agricultura de corte e queima, extração de madeira predatória e desmatamento para implementar extensas áreas para a pecuária tornaram-se as principais atividades de uso da terra em Paragominas e muitos municípios vizinhos (UHL et al, 1988).

A perda da vegetação foi acelerada entre os anos de 1983 a 1992 pela produção de gado, além de ser responsável pelo maior polo madeireiro do país em 1990 (VERISSIMO et al., 1992). Na mesma década foi introduzida a agricultura mecanizada e entre os anos de 2001 e 2006 houve a expansão do cultivo da soja e, como reflexo, a devastação desordenada e altas taxas de desmatamento até 2008 (PIKETTY et al., 2015). Após tanto desmatamento e degradação o Ministério do Meio Ambiente criou a lista dos municípios que mais desmatavam na Amazônia (Decreto nº 6321/2007). Em 2007, o ano do decreto, Paragominas já possuía 45% do seu território desmatado, quando o município foi inserido na lista dos maiores desmatadores da Amazônia (PIKETTY et al., 2015). A inclusão na *"lista vermelha"* dos municípios que mais desmatavam no país gerou uma limitação dos produtores rurais ao crédito e propriedades foram embargadas, impedido que comercializassem seus produtos, consequência do desmatamento ilegal (BRITO, 2019).

Em contrapartida, esse cenário de devastação, levou ao município a também ser incluído na lista de municípios amazônicos prioritários nas ações de prevenção, monitoramento e controle do desmatamento ilegal. Nesse cenário, graças à mobilização do poder público e empresários locais, foi lançado em fevereiro de 2008, o Projeto Paragominas Município Verde, primeiro município brasileiro na criação de alternativas sustentáveis de desenvolvimento e controle do desmatamento (OLIVEIRA et al., 2012). Com a proposta de ser uma iniciativa modelo, após três anos, o referido programa, foi expandido para outros municípios. No entanto, para que o município revertesse o cenário de maior devastador da Amazônia, foi necessário promover ações que buscassem o interesse dos proprietários de terra, principalmente na recuperação de sua reserva legal e/ou mata ciliar em cumprimento ao Código Florestal que, em muitos casos foi negligenciado no município (BRITO, 2019).

A partir das ações geradas, em 2010, Paragominas se tornou o primeiro município brasileiro a sair da lista dos que mais desmatavam na Amazônia, após dois anos engajados em práticas de melhorias da governança na prevenção e controle do desmatamento (SILLS et al., 2015). Em 2012, com a publicação do novo Código Florestal, a proposta de ser município verde condicionou a aderência do desmatamento ilegal zero, criação do Cadastro Ambiental Rural (CAR), como ferramenta no controle, monitoramento, planejamento ambiental e econômico e combate ao desmatamento, além do compromisso com o cumprimento da Norma. Em 2014, foi criada a lei municipal para a regulação da compensação da reserva legal, tornando-se

Paragominas pioneira em autorizar esse tipo de procedimento no estado do Pará (PIKETTY et al., 2015). Por ter diminuído consideravelmente suas taxas de desmatamento, haver criado ações sustentáveis, através da cadeia de suprimento e registrar mais de 80% de propriedades rurais (cadastro ambiental rural - CAR), passou a ser considerado como município verde (PIKETTY et al., 2015).

Todo esse resultado pode ser atribuído ao fortalecimento das relações entre os governos federal, estadual e local, tendo como participante principal e engajador a elite latifundiária no intuito de firmar parcerias com organizações da sociedade civil internas e externas e transformar a crise em oportunidade de transformação, sendo que essa modalidade híbrida, ainda é um desafio quando se busca oportunizar os diferentes setores da sociedade rural (VIANA et al., 2016).

1.3. Mineração: economia – desafios e oportunidades

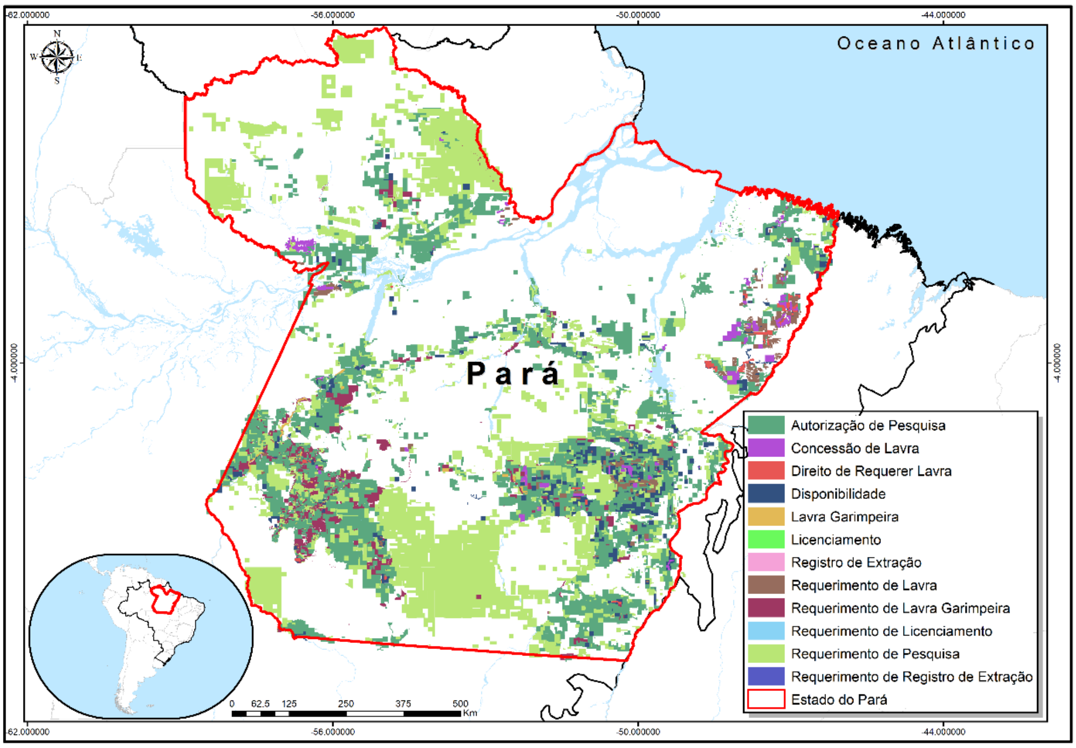
Os recursos minerais e energéticos são encontrados em áreas de floresta no mundo inteiro e têm sido demandados por serem a base para a fabricação de diversos produtos. No entanto, a extração dos recursos minerais demanda ações que causam impactos destrutivos sobre os ecossistemas naturais, sendo um dos motivos da preocupação global com o meio ambiente (WORLD RESOURCES INSTITUTE, 2014).

Em análise realizada por Ferreira et al.(2014), 20% das áreas de proteção integral no Brasil e terras indígenas estão sobrepostas em áreas de interesse minerário e, se tratando de Amazônia 8,3% estão dentro de Unidades de Conservação e 28,4% em terras indígenas.

A mineração é uma das grandes causadoras da degradação ambiental e o Pará detém a autorização de direito de lavra de vários minérios, contando com 7.268 mineradoras licenciadas em 2019 no país (ANM, 2019; **Figura 1**), sem contar com as extrações clandestinas que, por vezes, degradam ainda mais, por não possuir compromisso com determinações de mitigação de impactos.

Apesar da degradação, a mineração é uma atividade de utilidade pública, de interesse social, que, para o licenciamento, deve ser viável economicamente e ambientalmente, minimizando os impactos socioambientais e propondo ações de desenvolvimento local onde são instalados os empreendimentos. E, com o decorrer dos anos, em virtude de históricos de degradação ambiental, as mineradoras têm sido demandadas pelo desenvolvimento de metodologias eficientes de acordo com o novo cenário mundial, além do cumprimento legal, já estipulado no processo de licenciamento. Isto decorre do aumento da preocupação sobre questões globais em relação às mudanças climáticas e à percepção do quanto a floresta é necessária para a regulação de meios bióticos e abióticos.

Figura 2. Mapa da distribuição de concessões de lavra no estado do Pará em 2019



Fonte: Elaboração própria. Mapa da Amazônia Brasileira com o mapeamento dos minérios de lavras realizados pela Agência Nacional de Mineração – ANM).

Sabe-se que a mineração causa grande impacto ambiental, mas em contrapartida a Produção Mineral Brasileira (PMB) é responsável por contribuir com 1,4% do Produto Interno Bruto (PIB) brasileiro e representa um dos pilares da economia brasileira (IBRAM, 2019). Somente em 2017 o Brasil exportou mais de 403 milhões de toneladas de bens minerais gerando uma renda de US$ 32 bilhões. Os principais produtos exportados foram: minério de ferro (76%), cobre (18%), alumínio (2%), manganês (2%), caulim (1%), ouro (1%) e outros (2%) (IBRAM, 2019). No estado do Pará, dos US$ 15,608 bilhões em exportações totais em 2018, as indústrias de mineração e transformação mineral responderam por 88% deste valor, e juntas, exportaram US$ 13,725 bilhões, fazendo do setor mineral o grande vetor de crescimento do comércio exterior paraense, sobretudo devido a países como China, Malásia e Japão os três maiores mercados compradores de bens minerais produzidos no Pará (SINMINERAL, 2019).

Apesar da atividade de mineração trazer muitos benefícios econômicos e sociais, ela também promove impactos diretos e indiretos de diferentes naturezas sobre a área em exploração e seu entorno. Os impactos sobre o solo, vegetação e os recursos hídricos são observados na forma de alterações estéticas, físicas, químicas e biológicas. Dependendo das características da geologia, vegetação, relevo, solo e tipo de lavra e minério extraído, os impactos pedem ser severos (LONGO et al., 2011). Além dos danos causados pelo processo de escavações, principalmente em empreendimentos não licenciados, uma grande quantidade de resíduos de rochas e rejeitos é depositada na superfície. Os resíduos e resultados de degradação por mineração consistem tipicamente em: áreas desmatadas (59%), minas a céu aberto (20%), barragens de rejeitos (13%), pontas de resíduos (5%) e terras afetadas pela mineração (3%) (LEI et al., 2016). Cabe ressaltar que, durante a mineração de superfície, 2 a 11 vezes mais solo é degradado em comparação com a mineração subterrânea (MIAO et al., 2000).

1.4. A importância da atividade mineira na Amazônia brasileira: Economia e degradação

A mineração está presente no Brasil desde o século XVII quando expedições de bandeirantes paulistas descobriram ouro nas regiões de Mato Grosso e Minas Gerais, especialmente nas regiões de Vila Rica (Ouro Preto), Nossa Senhora do Carmo (Mariana) e Vila Real do Sabará (Sabará). Estas localidades receberam pessoas do país todo em busca de ouro (GUIMARÃES et al., 2018). A mineração é umas das atividades que mais degrada o meio ambiente (SONTER et al., 2014, ALVAREZ-BERRÍOS et al., 2015) e pode ser realizada de forma manual ou mecanizada, mas o executor deve realizar a atividade segundo uma série normas legais, para minimizar o impacto ao meio ambiente (Decreto nº 97.632, de 10 de abril de 1989). Segundo a Agência Nacional de Mineração (ANM) a produção mineral atual do país tem mais de 3 mil minas. A região Amazônica corresponde a cerca de metade do território brasileiro, entretanto somente cerca de 300 minas, menos de 10% do total das minas brasileiras, estão situadas na Amazônia (UMBERTO, 2019), e a metade dessas concessões estão concentradas no estado do Pará (MMA, 2019).

A Amazônia Legal possui 5.217.423 Km², distribuídos em nove estados, sendo 45,2% de seu território delimitado por áreas protegidas (WWF, 2018). Nela, existem 5.675 processos de exploração mineral (pesquisa e lavra) sobrepostos a Terras Indígenas e Unidades de

Conservação (UCs) de Proteção Integral na Amazônia Legal, onde 94% são pesquisas já autorizadas em UCs Federais, 26% em UCs Estaduais e 42% em Terras Indígenas e, em UCs de uso sustentável. Os títulos ativos ultrapassam 17 mil, porém, parte dessas autorizações encontra-se bloqueada pela União (WWF, 2018).

A mineração é caracterizada como uma indústria de base, que impulsiona outras oportunidades econômicas, com grande relevância econômica e social, significativa no dia-a-dia da sociedade, sendo matéria-prima de vários produtos, porém é um recurso finito. Atualmente são mais de 50 bens minerais com reservas conhecidas, sendo esse setor responsável por 4% do PIB brasileiro (ANM, 2019). Em 2017, os principais produtos exportados foram: minério de ferro, ouro, ferronióbio, cobre, bauxita, manganês, caulim, pedras naturais e de revestimentos, gerando cerca de 180 mil empregos diretos (IBRAM, 2019).

A classificação dos minerais explorados é realizada de acordo com o ciclo de vida, etapas de pesquisa, mineração e transformação mineral, diferentes impactos gerados, às vezes irreversíveis, e consequentemente, diferentes metodologias de mitigação de impactos e recuperação das áreas degradadas pela atividade. Grande parte da extração dos minérios localizados na Amazônia, utiliza-se da metodologia de minas a céu aberto (CONGILIO, 2014), como é o caso da mina de ferro em Carajás (Pará), caulim no Projeto Jari (Amapá), bauxita (alumínio) em Trombetas (Pará), cassiterita (estanho) em vários locais nos estados do Amazonas e Rondônia, e manganês na mina, hoje abandonada, na Serra do Navio, estado do Amapá e, por esse motivo, um dos impactos mais relevantes é a perda da vegetação.

As perdas da vegetação ultrapassam os limites operacionais e de lavra, onde são necessários áreas de apoio para viabilizar a extração, beneficiamento, transporte do minério, construção de infraestrutura, que podem chegar a 70% de perda de vegetação, além dos limites da concessão da mineração. No período de 2005 a 2015 foram contabilizados 11.670 km² de desmatamento devido à mineração, o que representa 9% de toda perda de floresta amazônica no período (SONTER et al., 2017). Esse motivo é um dos que coloca a mineração no foco das críticas de ambientalistas em todo mundo. Nos últimos cinco anos a negativa da atividade de mineração ganhou mais enfoque em virtude de dois desastres socioambientais ocorridos no estado de Minas Gerais com o rompimento das barragens de rejeito em Mariana (2015) e Brumadinho (2019). Dois desastres num intervalo de tempo muito curto e com consequências socioambientais graves.

1.5. Explorando o caulim na Amazônia brasileira

O caulim é um mineral não metálico constituído basicamente por caulinita, que pertence ao grupo das argilas, e tem muitas aplicações industriais. Possui cor branca por apresentar baixo teor de ferro. Trata-se de um mineral argiloso branco, não inflamável, não tóxico e que não apresenta reatividade química (IMERYS CAULIM, 2020). O caulim é um dos minerais explorados na região Norte e com grande influência na economia paraense (SINMINERAL, 2019), sendo o quinto minério mais exportado no Brasil, principalmente para os Estados Unidos, Canadá e Europa (IMERYS CAULIM, 2020). Sua exportação em 2018 foi de US$ 168 milhões, com 1,546 milhões de toneladas (SINMINERAL, 2019).

Pelo seu potencial econômico, há grande oferta e demanda de caulim em virtude de suas várias utilizações. A indústria papeleira absorve quase 50% de toda a produção mundial de caulim, onde o mineral é utilizado para preencher as fibras de celulose e cobrir a superfície do papel. Também é utilizado nas indústrias de cerâmicas, tintas, borrachas, polímeros, farmacêuticos, na construção civil e na indústria de fertilizantes (CEPEMAR- CENTRO DE PESQUISAS DO MAR, 1993). Entretanto, tal como os outros minerais, sua extração requer atividades de grande impacto ao meio ambiente (MME, 2009).

O caulim ocorre em todo o mundo e é considerado estratégico para a balança comercial do Brasil (IBRAM, 2019). Sua ocorrência se dá em virtude da liberação do alumínio por intemperismo a partir das rochas silicáticas primárias em planícies aluvionares, originando grandes depósitos de caulim. Na Amazônia brasileira o caulim é encontrado na Província Caulinítica do Rio Capim (AM e PA) e do Rio Jarí (PA) (MELFI, 2016). É explorado no Amapá pela empresa Jari Celulose e no Pará pela empresa Imerys. O processo de obtenção do caulim se inicia com a remoção da camada estéril e a extração do minério bruto. O método de lavra utilizado pela Imerys é a extração a céu aberto em aluvião-horizontal (stripping mine), com supressão total da vegetação, decapeamento, remoção de estéries, extração, carregamento e transporte para beneficiamento primário (MME, 2009; SILVA, 2014). A Imerys tem a maior planta de beneficiamento de caulim do mundo e 71% de participação na produção de caulim no Brasil, com duas minas no município de Ipixuna do Pará (PA) - Capim I e Rio Capim Caulim (SINMINERAL, 2019). Segundo o Anuário Mineral do Estado do Pará de 2017, o caulim possui uma reserva lavrável de 88.772.068 toneladas, e sua produção em 2016 foi de 2.830.254 toneladas, equivalente a R$ 685.592.476 (DNPM, 2017).

1.6. Como restaurar e monitorar a vegetação em áreas em processo de sucessão?

A intensificação das ações antrópicas sobre o meio ambiente, sem preocupações com sua sustentabilidade gera a diminuição da capacidade dos ecossistemas sustentarem suas funções, resultando em intensa degradação do meio ambiente. Essa situação impulsiona as ações em priorizar de recuperação e/ou proteção da biodiversidade, para o reestabelecimento da funcionalidade dos ambientes degradados (DAWSON et al., 2017).

A restauração ecológica, segundo definição da Society for Ecological Restoration International Science & Policy Working Group – SER (2004), é o processo de recuperação de um ecossistema que foi degradado, que pode ser condicionado na retomada completa à condição ambiental original, situação que na prática é difícil de ocorrer. É importante priorizar a recuperação das condições ecológicas para favorecer a sucessão natural (MARTINS, 2010), porém independentemente do método adotado, o monitoramento dos ecossistemas em restauração é fundamental e necessário para o acompanhamento do seu desenvolvimento.

Várias experiências estão sendo desenvolvidas na Amazônia. Estudo realizado por da Cruz et al., (2020), identificaram 405 projetos localizados em 191 municípios entre 1950 a 2017 no bioma Amazônia (estados do Acre, Amapá, Maranhão, Mato Grosso, Pará, Rondônia e Tocantins). Estas experiências vêm sendo gerenciadas por organizações governamentais e não-governamentais, empresariais e por agricultores familiares. Entretanto, a maioria dessas iniciativas não está publicada e, grande parte trata-se de projetos empresariais, envolvendo reflorestamento comercial, plantios nativos em resposta a licenciamentos ambientais, onde a área foi degradada pelo empreendimento (DA CRUZ et al., 2020).

Os empreendimentos de mineração possuem o desafio de "recriar" o solo a partir da desestruturação dos horizontes, com variação na estrutura, composição e função do ecossistema. Isto inclui a reconstrução de tipos de solo e o estabelecimento de espécies vegetais, considerando a diversidade e a sucessão ecológica, que em ambientes naturais ocorrem em longos períodos. (MACDONALD et al., 2015). Com todo esse processo de "recriação" do ambiente degradado, há várias consequências provenientes da desestruturação do solo, onde o procedimento de reconformação topográfica do terreno não consegue evitar a compactação e amassamentos das superfícies. Isto acaba influenciando diretamente no desenvolvimento da vegetação no processo de restauração, dificultando o desenvolvimento das raízes ao longo dos perfis do solo (SOUZA, 2018).

No processo de restauração pós-mineração, um novo ecossistema e um novo padrão de paisagem são formados, mas um longo tempo é necessário para que eles alcancem a estabilidade (LEI et al., 2016). Dentre as alternativas de restauração, a abordagem de engenharia ecológica e serviços ecossistêmicos (ES) são aplicadas na avaliação da restauração de áreas de mineração na perspectiva do desenvolvimento sustentável (LEI, et al, 2016). Em todo o processo deve-se considerar a restauração dos meios biótico e abiótico, aspectos da paisagem, como: práticas de caráter topográfico, edáfico, hídrico e vegetativo (SÁNCHEZ, 2010), objetivando a auto sustentabilidade, cumprimento dos objetivos ecológicos, econômicos e sociais (MACDONALD et al., 2015). Atualmente, o plantio de mudas utilizando espécies arbóreas é a metodologia mais difundida e consolidada no mercado, seguido pela condução da regeneração natural e em menor escala, a nucleação. Porém, devido à remoção dos horizontes do solo para extração do minério, com a descaracterização dos perfis do solo, diferentes metodologias podem ser aplicadas a cada realidade (RIBEIRO et al., 2019).

Para avaliar a eficiência da metodologia utilizada na recuperação das áreas mineradas é necessária uma avaliação contínua do desenvolvimento e dinâmica dos povoamentos vegetais por meio de indicadores, para que se possa realizar, caso necessário, intervenções que possibilitem o retorno à direção estabelecida inicialmente ou uma mudança de diretrizes que viabilizem a conclusão do processo de recuperação (HOWELL et al., 2012). Cabe ressaltar que, no caso da mineração, a restauração é realizada por motivos de exigência legal, podendo ser conduzidos, utilizando critérios como formação de corredores ecológicos, estudos de atração de fauna e indução da regeneração natural, que favorecem o processo de sucessão e manutenção da diversidade genética (ZUCCHI et al., 2018). Além disso, deve-se considerar a proteção e manutenção dos recursos hídricos (FILOSO et al., 2017), estoque de carbono (BUSTAMANTE et al., 2019), gerando benefícios para a biodiversidade (MATOS et al., 2020).

Quando se fala em Amazônia, com extensas áreas de florestas, porém com extensas áreas degradadas por diferentes tipos de uso do solo, ainda há desafios a serem enfrentados, necessitando o desenvolvimento de planos técnicos eficientes e financeiros viáveis, políticas públicas e instrumentos de monitoramento que possam avaliar a eficácia dos projetos de restauração (NUNES et al., 2020). No caso dos dois municípios estudados nessa tese, Paragominas e Ipixuna do Pará, ambos com atividade minerária e com os danos ambientais causados pela atividade, é necessário a avalição dos componentes ecológicos. No primeiro capítulo da tese é abordado o município de Paragominas. O município já possui o sistema de cadastro ambiental rural (CAR) bem consolidado, com ações de minimização de impactos e interesse de mudar seu histórico degradador. Assim, é possível a realização de um estudo modelo para uma proposta de restauração do município, que posteriormente poderá ser replicado a Ipixuna, área alvo dos capítulos dois e três, na qual é avaliada uma metodologia de restauração em área de mineração.

1.7. Marco Legal da restauração florestal

1.7.1 Território Nacional

- A Política Nacional do Meio Ambiente (Lei nº 6.938/1981) no seu artigo 4° reforça que os recursos naturais deverão ser utilizados de forma racional a fim de garantir a manutenção do equilíbrio ecológico.
- A Resolução nº 001, de 23/01/1986, foi criada para estabelecer os critérios básicos e diretrizes gerais para a avaliação de impacto ambiental. Todo o empreendimento de mineração tem a obrigatoriedade de elaborar planos de recuperação de forma criteriosa, com utilização de mão-de-obra tecnicamente qualificada, com conteúdo em atendimento às premissas do Estudo de Impacto Ambiental (EIA) e concatenado com os demais planos do Programa de Controle Ambiental (PCA), que são partes do processo de licenciamento do empreendimento.
- A base de todas as diretrizes políticas do país baseia-se na Constituição Federal de 1988, e em seu art. 225, estabelece que:
- “...Todos têm direito ao meio ambiente ecologicamente equilibrado, bem de uso comum do povo e essencial à sadia qualidade de vida, impondo-se ao Poder Público e à coletividade o dever de defendê-lo e preservá-lo para as presentes e futuras gerações...”
- No parágrafo 2° do mesmo artigo retrata a obrigatoriedade de recuperação dos ecossistemas explorados pelos empreendimentos de mineração.”
- Para estabelecer as diretrizes do PCA para o item de avaliação do meio biótico, é elaborado o Plano de Recuperação de Áreas Degradadas – PRAD. O PRAD teve sua origem no artigo 225, da Constituição Federal de 1988, e no Decreto-Lei n. 97.632/89, que

regulamentou a Lei n. 6.938/81, obrigando a recuperação da área degradada como parte do Relatório de Impacto Ambiental, empregado de forma preventiva ou corretiva, em áreas degradadas por ações de mineradoras.

- Em 02/12/1998, foi publicada a Lei nº 9.605, conhecida como Lei de Crimes Ambientais que dispõe sobre as sanções penais e administrativas derivadas de condutas e atividades lesivas ao meio ambiente, e dá outras providências.
- Decreto nº 3.420, de 20/04/2000, publicada com o objetivo da criação do Programa Nacional de Florestas – PNF e, em seu Art.2ª, estabelece vários objetivos, dentre eles: (II) fomentar as atividades de reflorestamento, notadamente em pequenas propriedades rurais; (III) recuperar florestas de preservação permanente, de reserva legal e áreas alteradas; (IV) apoiar as iniciativas econômicas e sociais das populações que vivem em florestas; (V) reprimir desmatamentos ilegais e a extração predatória de produtos e subprodutos florestais, conter queimadas acidentais e prevenir incêndios florestais.
- A Lei nº 9.985/2000 (SNUC), que em seu art. 2º, faz distinção entre um ecossistema "recuperado" e "restaurado"; que recuperar significa restituir um ecossistema degradado a uma condição não degradada, que pode ser diferente de sua condição original, e restauração, é a restituição de um ecossistema degradado o mais próximo possível da sua condição original.
- O Programa Nacional de Florestas – PNF, criado através do Decreto nº 3.420/2000, tem por objetivos: fomentar as atividades de reflorestamento em pequenas propriedades rurais e recuperar florestas de preservação permanente, de reserva legal e áreas alteradas.
- Lei nº 11.284, de 2 de março de 2006, normatiza o sistema de gestão florestal em áreas públicas e com a criação do órgão regulador (Serviço Florestal Brasileiro) e do Fundo de Desenvolvimento Florestal, que em seu artigo 31, item IV, estabelece que empreendedor deve recuperar as áreas degradadas, quando identificado o nexo de causalidade entre suas ações ou omissões e os danos ocorridos.
- Instrução Normativa IBAMA Nº 04, de 13-04-2011, em seu Art. 1º estabelece procedimentos para elaboração de Projeto de Recuperação de Área Degradada - PRAD ou Área Alterada.
- O novo Código Florestal (Lei nº 12.651/2012) estabelece em diversos artigos (artigos 1º-A, 7º, 17, 41, 44, 46, 51, 54, 58, 61-A, 64, 65 e 66) ações para que o setor público e a sociedade civil promovam a recuperação de áreas degradadas.

- Instrução Normativa ICMBio nº 11, de 12/11/2014, estabelece procedimentos para elaboração, análise, aprovação e acompanhamento da execução de Projeto de Recuperação de Área Degradada ou Perturbada - PRAD, para fins de cumprimento da legislação ambiental.
- Decreto nº 9.179, de 23/10/2017, que altera o Decreto n o 6.514/2008, que dispõe sobre as infrações e sanções administrativas ao meio ambiente e conversão de multas, considerando em seu artigo 140, a recuperação como um dos serviços de preservação, melhoria e recuperação da qualidade do meio ambiente.
- Instrução Normativa ICMBio nº 2, de 19/02/2018, dispõe sobre os procedimentos relativos à conversão de multas simples em serviços de preservação, melhoria e recuperação da qualidade do meio ambiente no âmbito do Instituto Chico Mendes.

17.2 No âmbito do estado do Pará

- Política Estadual Florestal (Lei n° 6462/2002) define que a revegetação dos ecossistemas alterados deverá prioritariamente ser executada com implantação de espécies nativas, obedecendo aos critérios econômicos e sociais. No caso de violação da Reserva Legal das propriedades rurais, os proprietários ficam obrigados a recompor a vegetação mediante três alternativas: plantio direto de espécies nativas ou exóticas em 1/10 da área total a cada três anos; condução da regeneração natural e compensação da reserva legal com a aquisição de outra propriedade da mesma microbacia, desde que tenha a mesma importância ecológica e extensão.
- Instrução Normativa nº 6, de 04/04/2008, que dispõe sobre o licenciamento ambiental para fins de reflorestamento e exploração de floresta plantada em áreas degradadas.
- Instrução Normativa nº 9, de 22/06/2009, que disciplina a nova regulamentação do Cadastro Ambiental Rural - CAR e define os procedimentos para o Licenciamento Ambiental de Atividades Rurais – LAR no Estado do Pará, onde estabelece obrigações de recuperação/recomposição da Área de Reserva Legal – ARL e/ou da Área de Preservação Permanente – APP.
- Lei Ordinária nº 7.369, de 29/12/2009, sobre a recomposição de áreas desmatadas situadas em reserva legal no âmbito do Estado do Pará, mediante o plantio de espécies nativas frutíferas de porte arbóreo e palmáceas, em propriedades comprovadamente desmatadas antes do Macrozoneamento Ecológico-Econômico do Estado do Pará, com recuperação a cada três anos, de no mínimo 1/3 da área total necessária a sua complementação.

- As leis estaduais n.º 7378/2010 e 7604/2012 instituíram o Zoneamento Ecológico-Econômico - ZEE como base para o planejamento de políticas, programas e projetos para ordenação do território no estado do Pará. O ZEE deve ser observado para implementação de programas de reflorestamento, a fim de direcionar as ações em áreas ambientalmente sensíveis.
- Na esfera estadual, a Lei 7381/2010 dispõe sobre a recomposição da cobertura vegetal das matas ciliares do estado do Pará, onde estabelece a largura mínima das faixas marginais de corpos d'água e determina que a especificação técnica a ser utilizada e o prazo de execução não poderá ser superior a 5 anos.
- Decreto nº 54, de 29/03/2011, que institui o Programa de Municípios Verdes - PMV no âmbito do Estado do Pará, tendo como um dos objetivos a redução do desmatamento e degradação, promoção da recuperação ambiental e a conservação dos recursos naturais.
- Instrução Normativa nº 6, de 03/07/2013, que trata sobre o licenciamento para a atividade de lavra garimpeira de ouro no Estado do Pará.
- Instrução Normativa nº 1, de 15/02/2016 que dispõe sobre os procedimentos e critérios, para adesão ao Programa de Regularização Ambiental do Pará – PRA PA, que em seu Art. 3º exige como um dos documentos necessários para regularização ambiental o Plano de Recuperação de Áreas Degradas ou Alteradas - PRADA, acompanhado de cópia da ART do responsável pela sua elaboração.

Normas e diretrizes foram desenvolvidas no estabelecimento de procedimentos e sanções sobre o tema recuperação de áreas degradadas dentro do território brasileiro, que são primordiais para o desenvolvimento das atividades ligadas à restauração. É notório e comprovado que a legislação brasileira abrange vários critérios que estabelecem a obrigatoriedade de restauração, porém, em se tratando de bioma Amazônia, ainda há carência no estabelecimento de diretrizes, indicadores e metodologias específicas.

2. OBJETIVO GERAL

Considerando a situação atual da Amazônia com relação à perda da vegetação original e a necessidade de restaurar essas áreas, a presente tese tem por objetivo avaliar o potencial de restauração florestal na Amazônia brasileira, com enfoque na região do nordeste paraense, para propor métodos de restauração eficientes para a realidade da mineração.

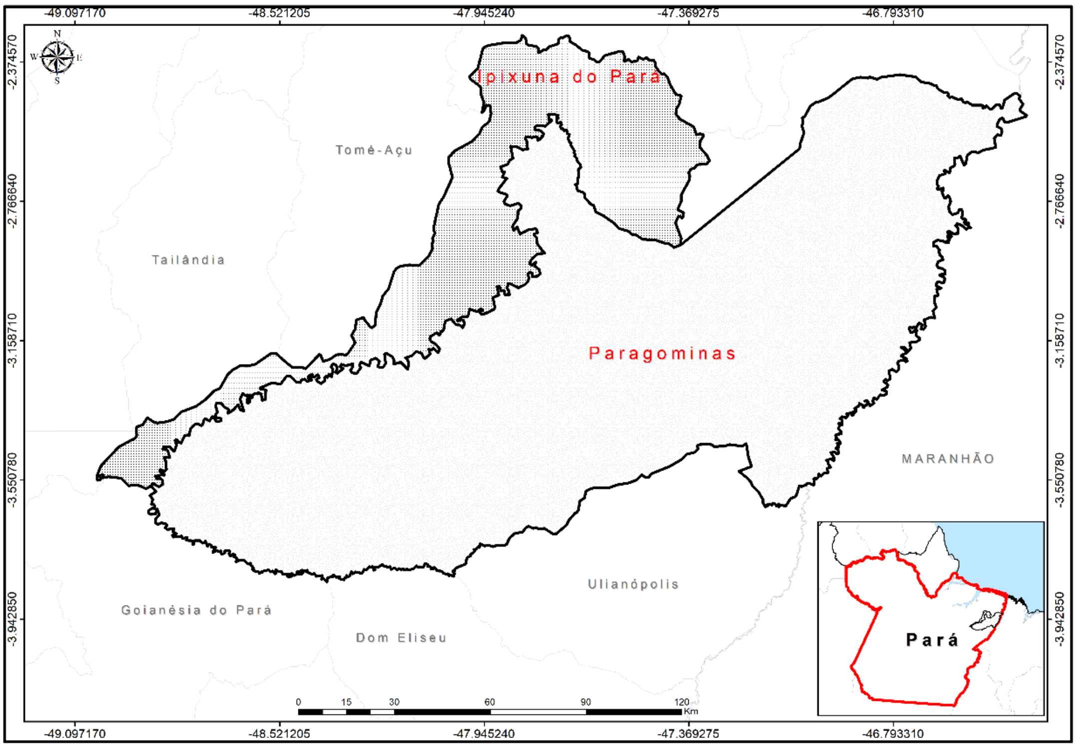
3. OBJETIVOS ESPECÍFICOS

- Avaliar a possiblidade de restaurar áreas de preservação permanente (rios e nascentes) em propriedades rurais que possam servir de corredores ecológicos, aumentar a biodiversidade e fomentar a redução do desmatamento;
- Avaliar a eficiência de um método de restauração através da composição florística de espécies florestais e estoque de serapilheira em área degradada por mineração de caulim.
- Avaliar a eficiência de um método de restauração através dos atributos químicos do minesoil, em função de diferentes técnicas de adubação sob processo de restauração após mineração de caulim.

4. ÁREA DE ESTUDO

Esta Tese de doutorado está estrutura em seis capítulos, divididos da seguinte forma: *a)* Primeiro Capítulo - Introdução Geral da Tese; *b)* Segundo, Terceiro e Quarto Capítulos de pesquisa da Tese, mostram resultados de pesquisa desenvolvida durante o doutorado e são apresentados na forma de artigos científicos; c) Quinto Capítulo – Discursão Geral e c) Sexto Capítulo – Conclusões. O primeiro capítulo de pesquisa (Capítulo 3) da Tese foi realizado no município de Paragominas, PA e o segundo e terceiro capítulo de pesquisa (Capítulo 4 e Capítulo 5) foram realizados com dados coletados na Empresa Imerys Caulim, município de Ipixuna do Pará, PA (**Figura 3**).

Figura 3. Área de Estudo, municípios do estado do Pará



Fonte: Elaboração própria. Bases de dados do IBGE – Instituto Brasileiro de Geografia e Estatística (https://www.ibge.gov.br/geociencias/informacoes-ambientais/15842-biomas.html).

5. QUESTÕES CIENTÍFICAS E HIPÓTESES

Capítulo 2: Áreas prioritárias para restauração em áreas de preservação permanente de propriedades rurais na Amazônia brasileira.

Questão: A seleção de áreas prioritárias em áreas de preservação permanente (APPs) degradadas auxilia na diminuição do passivo ambiental das propriedades rurais?

Hipótese: A seleção de áreas prioritárias para restaurar APPs de propriedade rurais além de cumprir com a obrigatoriedade legal, contribuem com a formação de corredores ecológicos entre as propriedades.

Capítulo 3: Restauração após mineração de caulim por meio de trincheiras: efeitos da fertilização orgânica no desenvolvimento das plantas.

Questão: O desenvolvimento das plantas é influenciado pelos diferentes tipos de adubação orgânica em área pós-mineração de Caulim?

Hipótese: Considerando que o esterco bovino possui propriedades químicas e orgânicas a serem incorporadas na fertilização do solo, sua utilização proporciona maior crescimento das plantas nas trincheiras do plantio.

Capítulo 4: Propriedades do solo sob diferentes fertilizações orgânicas em área de restauração após mineração de caulim na Amazônia Oriental

Questão: Diferentes tipos de adubação favorecem o desenvolvimento dos atributos físicos e químicos do solo e o desenvolvimento das espécies florestais?

Hipótese: A adubação orgânica com esterco bovino aplicada na cova favorece melhor desempenho dos atributos físicos e químicos do solo.

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CAPÍTULO II: PRIORITY AREAS FOR RESTORATION IN PERMANENT PRESERVATION AREAS OF RURAL PROPERTIES IN THE BRAZILIAN AMAZON

(Artigo aceito na revista Land Use Policy)

ABSTRACT

Environmental degradation due to the misuse of natural resources has drastically changed landscapes in the Amazon. At the same time, discussion, knowledge, and actions on the conservation of forest remnants and restoration of degraded environments have increased worldwide. In the present study, rural properties in Paragominas, a municipality under intense land use change in the Brazilian Amazon, were analysed with the following objectives: (1) to evaluate the process of landscape change over the last 36 years (1984-2020); (2) to identify degraded environments within legally established permanent preservation areas (PPAs); and (3) to map environmental liabilities in degraded rural properties which, according to environmental regulations, must be recovered. Deforestation and land use were classified using satellite imagery from Landsat-5 and Sentinel-2 sensors. Shuttle Radar Topography Mission (SRTM) imagery was used to identify and map PPAs using geoprocessing tools. The priority areas for restoration were defined considering: a) the environmental liabilities of each rural property; b) the remnant forest in each rural property; c) the rural properties' boundaries; and d) the degraded PPAs in each rural property. Deforestation followed by land use change in Paragominas' territory increased from 12% (2,336 km^2) in 1984 to 45% (8,783 km^2) in 2020. Its water network had 20,149 km of rivers and 15,824 springs, and of this total, 4,416 km of rivers and approximately 6,157 springs were in areas under pressure (agriculture, pasture, urban areas and deforested areas). The environmental liabilities identified totalled 638.85 km^2, which, according to environmental regulations, must be recovered. For this reason, when producers protect PPAs in their properties, they also conserve soil and water resources as well as contribute to biodiversity maintenance. Despite the consistent reduction over the last few years, forest loss and degradation in the Brazilian Amazon have begun to increase again under President Bolsonaro's current government. In his statements, he has made it clear that he has no interest in the environment. For example, illegal fires in the Brazilian Amazon increased substantially in 2019, his first year in office, and this is probably a consequence of his "economic incentive policy".

Keywords: Amazon; rural properties; environmental liabilities; land use change; deforestation.

1. INTRODUCTION

Most of the remaining reserves of current rainforests in the world are in the Brazilian Amazon (SFB, 2010; Aragão, 2012). This biome encompasses one of the largest plant communities (ter Steege et al., 2013), which is estimated to hold ca. 50,000 species (Hubbell et al., 2008) and has a crucial role in global climate regulation (Nobre et al., 2016; Khanna et al., 2017). The region also plays a key role in carbon storage and in the planet's hydrological cycles (Fauset et al., 2015). However, these features are threatened by unsustainable anthropogenic activities (Solomon et al., 2007; Kindermann et al., 2008; Hansen et al., 2013). Among such activities, deforestation is the main force of environmental degradation (Azevedo-Ramos, 2018). Deforestation in the Brazilian Amazon has intensified from the 1970s onwards (Araujo, 2009) due to the Brazilian federal government's policy to offer rural credit for large entrepreneurs in an attempt to bring economic development to the region (Reydon, 2015). This has resulted in large deforested areas for agro-industrial, silvicultural and infrastructure projects (Hall, 1991; Kolk, 1998).

Paragominas was one of the Amazonian municipalities that were intensely degraded during the "economic development" period resulting from the Brazilian government's policies in the 1970s. Founded in 1965, it was one of the largest cattle producers between 1983 and 1992, as well as the country's largest timber producer in 1990 (Veríssimo et al., 1992). Logging may increase the economic viability of a given region (Barber et al., 2014); nonetheless, this activity may result in illegal deforestation emerging from irregularities in the environmental sector (van Solinge, 2010). Reduction in forest cover brings significant losses to biodiversity and decline in the quantity and quality of natural resources (Cardinale et al., 2012). These activities generate environmental liabilities, which are impacts on the environment due to a given economic activity. As a consequence of this, companies or landowners must offset these impacts caused to nature (Soares-Filho et al. 2014). The recovery of environmental liabilities is in the Brazilian environmental policy under the Brazilian Forest Code (Law no. 12,651/2012).

After intense environmental degradation processes in many municipalities in the Brazilian Amazon between the 1970s and the 1990s (Weinhold, 2015), other government policies, including programs and projects for recovery of degraded areas, have been implemented in the region (Brancalion, 2015). In this way, research groups from universities; national, international and non-governmental organisations; public agencies and even the private sector began to make and implement environmental recovery projects. Since then, techniques and planning strategies have been designed to assist recovery actions in degraded areas in the Brazilian Amazon (Rodrigues & Gandolfi, 2009).

In recent decades, forest restoration methods have been proposed (Martins et al., 2020), embracing the management of the micro watershed (De Andrade, 2005). Riparian forests (riparian zones), for example, have been prioritised in the Brazilian public environmental policies due to their temporal and spatial dynamics and their vegetative characteristics (Fremier, 2015; De la Fuente et al., 2018). Hence, a consistent strategy for biodiversity restoration of degraded ecosystems should be based on the concept of riparian ecosystem integrity on the watershed scale, especially in the springs of watercourses (Zakia, 2009). Restoration of riparian forests changes these areas into ecological corridors, interconnecting forest fragments and facilitating animal transit that promotes seed dispersal with gene exchange and the consequent perpetuation of plant species (Rockström et al., 2009; Steffen et al., 2015).

Several environmental studies aimed to detect priority areas for restoration use different approaches and models in the multi-criteria analyses that lead to satisfactory results (Francisco et al., 2008, Canto-Perello, 2018). For this reason, the use of GIS (Geographic Information System) tools in the evaluation of methods to detect priority areas for conservation and/or restoration has been increasingly adopted (Francisco et al., 2007). Due to its immense territorial extent, the Brazilian Amazon demands constant supervision with GIS information to monitor its vast areas (Matricardi 2005; Asner et al., 2006).

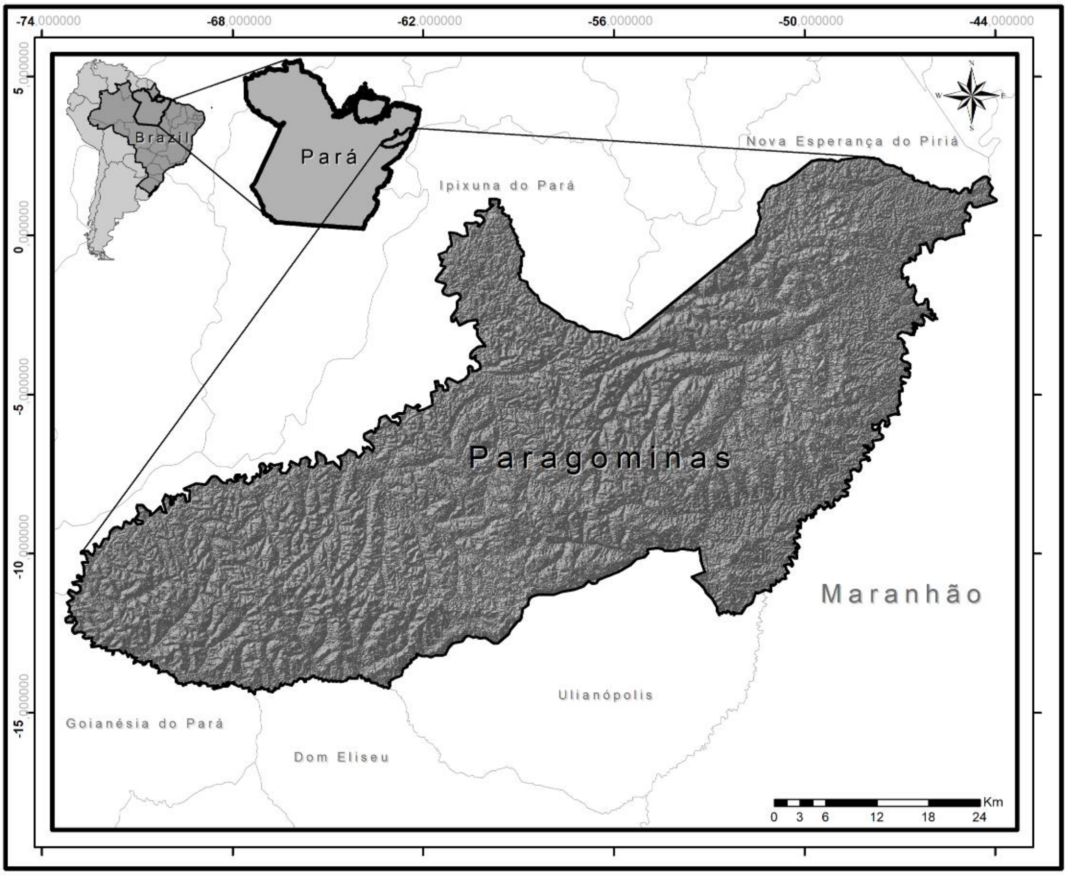
Considering the vast areas in the Brazilian Amazon and access difficulty, we present the following question: Are geospatial analyses adequate tools to identify and map landscape changes, which can be an important information source for decision-makers? The hypothesis for this question is: Mapping degraded environments in areas of permanent preservation is adequate to identify priority areas for forest restoration and the establishment of ecological corridors in the Brazilian Amazon. The answer to that question and the evaluation of the formulated hypothesis will provide tools to better define areas to be restored and conserved in the Brazilian Amazon. In this context, the present study aimed: (1) to evaluate the process of landscape change in the last 36 years; (2) to identify degraded areas that should be permanently preserved (i.e. rivers, springs and slopes > 45º); and (3) to map environmental liabilities in rural properties in the municipality of Paragominas in the Brazilian Amazon.

2. METHODS

2.1 Characterisation of the study area

The municipality of Paragominas was chosen as model for the Brazilian Amazon in this study (**Fig. 1**). Paragominas is located in northeastern Pará state, Brazil, on a territory of 19,465 km² which was originally covered with dense ombrophilous forest. The predominant soil type is yellow latosol, and the climate is hot and humid, with an average annual temperature of 26 ºC. Air humidity and annual rainfall are, on average, 80% and 1,800 mm, respectively, with a rainy season between December and May, and a dry season between June and November (EMBRAPA, 1988).

Fig. 1. Municipality of Paragominas' territory, Pará state, Brazilian Amazon



2.2 Landscape change (1984 to 2020)

To evaluate land use in Paragominas, deforested areas that had been converted into other uses were classified using satellite imagery from Landsat-5 sensors as of July 1984 and from Landsat-8 as of August 2020, which is available at: https://glovis.usgs.gov/app/.

The image classification method used was the same as that by Da Cruz et al., (2019), the Maximum Likelihood algorithm (Maxver). This is the supervised classification method most often utilised in remote sensing (Queiroz et al., 2004), mainly to classify secondary vegetation and forest classes. Also, some classes are confusing and difficult to identify (Pereira, 2012; Reis et al., 2017). Maxver considers the weighting of the distances between the averages of the digital levels of the classes and the pixel, using statistical parameters, that is, it considers the normal probability distribution for each class. Each pixel is, therefore, assigned to the class that has the highest probability. For this reason, a large number of sample pixels are required for each region to be classified. This method assumes that the analyst has minimal knowledge of the study area, since it is necessary to select the classes to be mapped *a priori*, collecting a greater number than one hundred pixels for each class in order to have mapping representativeness (Crosta, 1999). Thus, land use classes were generated, and samples of the areas in the image were classified into seven different classes: a) forest, b) secondary forest, c) pasture, d) agriculture, e) deforestation, f) urban area and g) hydrography. The images were classified from the samples selected for each use class, using the ENVI 4.7 software.

Finally, a confusion matrix was used to estimate the accuracy of the 2020 satellite image classification (Landis & Koch, 1977). A total of 1,555 points were evaluated (**Fig. S1;** supplementary material) in the confusion matrix to determine the producer's precision (data percentage from a correctly classified class, *producer's accuracy %* - equation 1) and user's precision (data percentage from a correctly photointerpreted class - equation 2). Such precision is determined by calculating the ratio between the correctly and poorly classified data. The Kappa index (equation 3) was generated to test significance and to compare with overall accuracy (equation 4), according to Congalton (1991), as well as to calculate the commission and omission error, using equations 5 and 6.

$$P.acc. = \frac{X_{ii}}{X_{+i}} \times 100 \quad (1) \qquad U.acc. = \frac{X_{ii}}{X_{i+}} \times 100 \quad (2)$$

$$K = \frac{N \sum X_{ii} - \sum X_{i+} X_{+i}}{N^2 - \sum X_{i+} X_{+i}} \times 100 \quad (3) \qquad O.acc. = \frac{\sum X_{i}}{N} \times 100 \quad (4)$$

$$C.error = \frac{X_{+i} - X_{ii}}{X_{+i}} \times 100 \quad (5) \qquad O.error = \frac{X_{i+} - X_{ii}}{X_{i+}} \times 100 \quad (6)$$

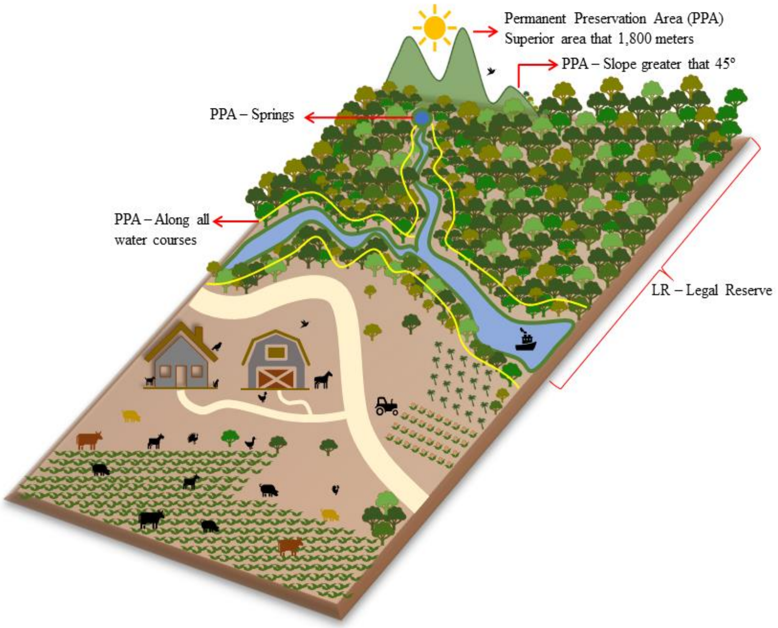
Where: *P.acc.* = Producer's accuracy %; *U.acc.* = User's accuracy %; *K* = Kappa index %; *O. acc.* = Overall accuracy %; *C. error* = Commission error %; *O. error* = Omission error %; X_{ii}

= Total of pixels classified in the expected class; X_{+i} = Total of pixels (vertical line); X_{i+} = Total of pixels (horizontal line); N = Total number of samples.

2.3 Mapping permanent preservation areas

In this study, permanent preservation areas (PPAs) were considered according to the Brazilian Forest Code (Law no. 12,651/2012), namely: i) springs, which must have a buffer zone of at least 50 meters; ii) vegetation along water courses, with a buffer zone that depends on the river width (**Fig. S2;** supplementary material); and iii) hillsides sloping more than 45º (**Fig. 2**). PPA delimitation was performed by the ArcGis 10.1 software using buffer and slope tools (Esri, 2012). PPAs (rivers, springs, and slopes) were obtained from the processing of SRTM imagery, available at: http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp.

Fig. 2. Model of a rural property in the Brazilian Amazon according to the Brazilian Forest Code (Law no. 12,651/2012). Every property larger than four fiscal modules must preserve the permanent preservation areas (PPAs) and the legal reserve (LR), depending on the municipality's characteristics, where one fiscal module can vary from 5 to 100 hectares.



2.3.1 Mapping of rivers and springs

Through the processing of SRTM images, a Digital Elevation Model (DEM) was generated to define water flows, using the Flow Direction tool available in ArcGis 10.1 (Esri, 2012). The values belonging to the adjacent raster cells may contain errors; therefore, it is necessary to correct the SRTM data using the Sink tool, which identifies possible imperfections in the raster. For imperfection correction, Fill (ArcGis tool) was used, and, thus, a new DEM and a new Flow Direction model were generated with the corrected raster values. Hence, the accumulated water flow was processed. Drainage extraction in the municipality's area was performed by map algebra. It was necessary to generate a threshold to identify how many adjacent pixels should form rivers. In this case, 500 pixels were selected using the CON (Conditional) function.

When the pixel value of the flow accumulation raster is greater than 500, it must be replaced by 1, otherwise it is transformed into NODATA. With this condition, all raster cells with values greater than 500 were considered in a new raster, and the other cells were transformed into NODATA. The calculation was done using the expression "Con" ("FLOW_ACCUMULATION.tif"> 500, 1), and finally the raster was converted into a shapefile. After the river identification, springs were extracted using the shapefile of newly classified rivers, by the ArcGis 10.1 Feature Vertices to Point tool.

2.3.2 Slope classification

Slope attributes were classified according to the processing of SRTM imagery and calculated by the ArcGis 10.1 Slope tool. Using ArcMap with the Spatial Analyst and 3D Analyst extensions, the Slope tools were run to generate a Slope raster. Then, the Reclassify tool was used to reclassify the slope into six categories: 0º - 5º; 6º - 10º; 11º - 20º; 21º - 30º; 31º - 44º and > 45%. After such procedures, features with a slope below 45° in rural properties were eliminated. The Brazilian Forest Code defines all hillsides with slopes greater than 45º as PPAs (Brasil, 2012).

2.4 Mapping of environmental liabilities in rural properties

2.4.1 Boundaries of Rural Properties

According to the Brazilian Forest Code, all rural properties in Brazil must be registered in environmental agencies at the state or municipal level, through a Rural Environmental Registry (abbreviated as CAR in Portuguese). This instrument assists the public administrative power with the environmental regularisation of properties. The vector base of rural properties in the municipality of Paragominas, originated from the National System of Rural Environmental Registration (SICAR; http://www.car.gov.br/publico/imoveis/index), is available free of charge by the Brazilian Forest Service (updated on February 18th 2020).

On the SICAR system, we identified 2,559 rural properties registered in the municipality of Paragominas, classified as *i)* assets: **active,** with the obligations to update the registered information, verified after analysis; *ii)* **pending**, when there is an incorrect declaration or overlapping of the rural property with indigenous lands, conservation lands, public lands, areas considered to be impediments, embargoed areas or areas overlapping with other rural properties, and *iii)* **cancelled**, when the information declared is totally or partially false, misleading or omitted. Once active properties were identified, properties overlaps were excluded, and properties were selected as: > 4 fiscal modules and < 4 fiscal modules (**Fig. S3;** supplementary material). A fiscal module is an agrarian quantification used by Brazilian agencies, established by Law no. 6,746/1979. It is expressed in hectares, and its area depends on each municipality, varying from five to 110 ha. In Paragominas, each fiscal module is equivalent to 55 ha. According to the New Forest Code, all rural properties with less than four fiscal modules are exempt from the obligation to comply with the Legal Reserve (LR), which is the obligation to maintain 50% of their property with vegetation, (Law no. 12,651/2012).

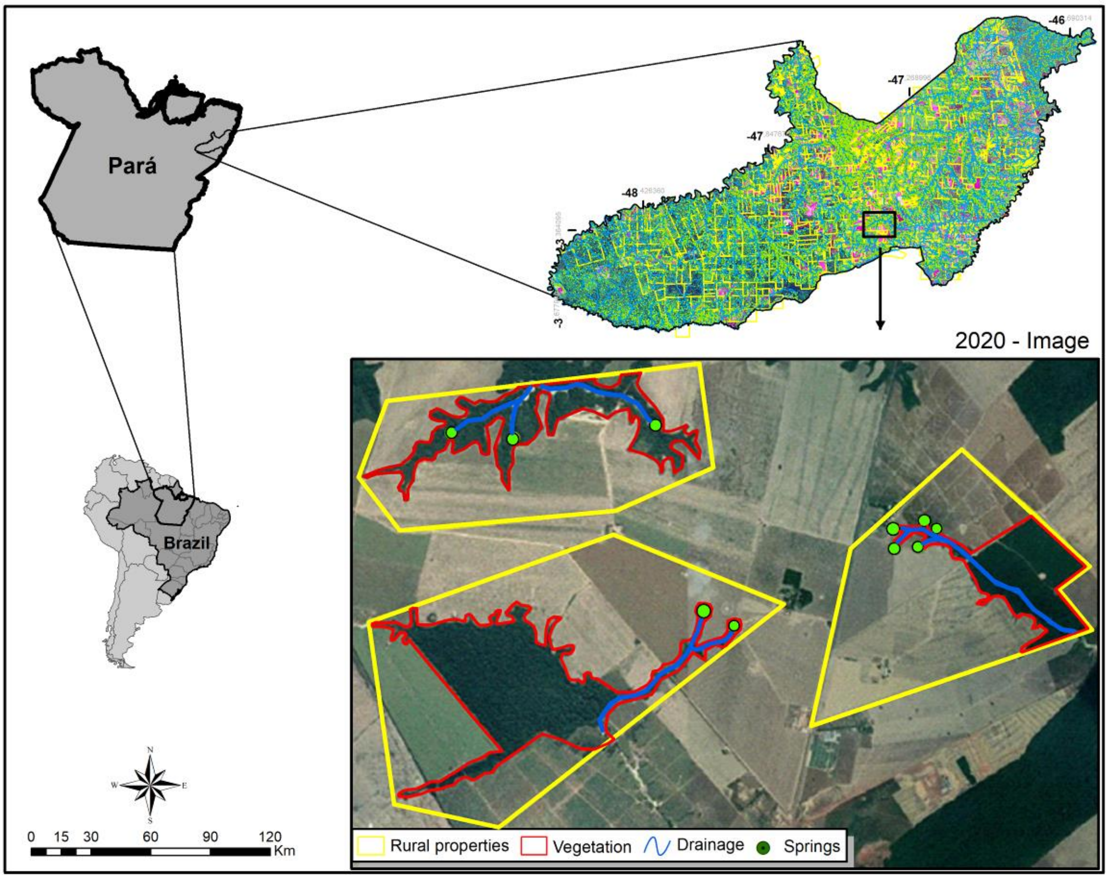
CAR contains all information about the rural property, so it must include the extension of the LR area, which is the area of the rural property that must be legally covered with natural vegetation. In LR, according to the Brazilian Forest Code, sustainable economic activities are specifically permitted for each biome. Thus, the percentage of a property's area that must be registered as LR varies according to the biome and the region in Brazil. In the Amazon biome, for example, this value is 50% or 80% of the property's total area, depending on two criteria: *a)* When the state's Ecological-Economic Zoning has been approved and more than 65% of its territory is covered with indigenous lands and nature conservation areas under public domain, *b)* When the municipality has more than 50% of its area in the same situation mentioned in “a”. In Paragominas the properties must present an LR of 50%. In this study, all properties in the municipality registered in CAR were mapped, including those with an area of less than four fiscal modules.

2.4.2 Classification of priority areas for restoration

In order to propose priority areas for forest restoration, the following was considered: *i)* Mapping of PPAs (rivers, springs, and areas with a slope greater than 45º); *ii)* Mapping land use and coverage to identify areas with vegetation in all rural properties; and *iii)* Identification of rural properties’ boundaries. After the identification of rivers and springs in the whole municipality, forest remnants to be preserved were defined. This was done in compliance with the protection watershed regulations (Brazilian Forest Code, Art. 4), maintaining 50-m and 30-m buffer zones along rivers and waterways, respectively.

From the classified imagery of use and coverage for the municipality of Paragominas, PPAs were mapped within the rural properties, using the CAR database to calculate LR, the percentage of vegetation remaining in the property and its environmental liability. Priority areas for restoration were proposed in rural properties with degraded PPAs and an LR of less than 50%. Vegetated areas were also merged with the selected priority areas in order to compose ecological corridors (**Fig. 3**).

Fig. 3. Illustration of rural properties in the municipality of Paragominas, Brazilian Amazon, with their respective vegetation areas and permanent preservation areas - PPAs (drainage and springs)



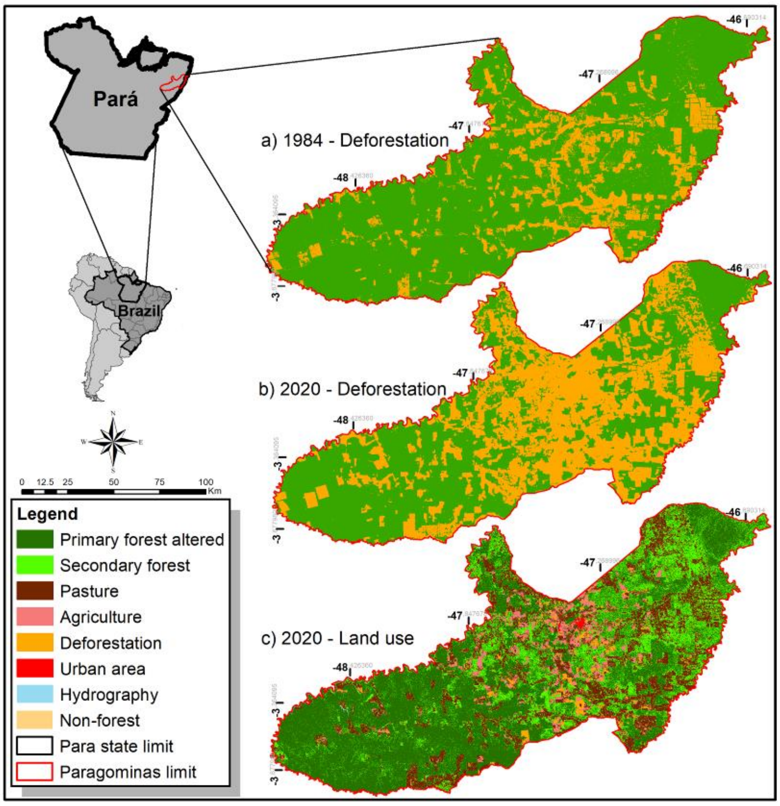
Principal Component Analysis (PCA) was performed in order to visualise and explain the relations between priority areas for restoration in rural properties and the potential factors that can generate differences among variables. PCA can be an understanding tool to reduce the dimensionality of the data matrix, facilitating its visualisation. It is expected that a small number of principal components can explain most of the variance with no relevant loss of information (Naes, 1991). The results were plotted using the autoplot by the R software, version 3.6.3 (ggplot2; cran.r-project.org/web/packages/ggplot2).

3. RESULTS

3.1 Landscape change over the last 36 years (1984 - 2020)

Since the municipality’s foundation in 1965, Paragominas’ territory has been widely deforested with rapid land use change into agriculture and livestock. According to the classification carried out in this study, 12% (2,336 km^2) of the municipality had already been deforested before 1984 (**Fig. 4a**). This percentage increased significantly in the following years, reaching 37% (7,202 km^2) in 2000 and 45% (8,783 km^2) in 2020 (**Fig. 4b**). In 36 years (1984-2020), deforestation in Paragominas' territory increased by 276% (6,447 km^2).

Fig. 4. Classification of satellite imagery in the municipality of Paragominas, Brazilian Amazon, using the Maximum Likelihood (Maxver) method. Images were classified from the samples selected for each use class, using the ENVI 4.7 software. The classifications resulted in a) deforested area by 1984; b) deforested area by 2020; and c) classification of land use and cover in 2020.



Results of the 2020 satellite imagery classification showed seven land use classes. According to the analysis, Paragominas presented 47.1% (9,188 km^2) of altered primary vegetation, 22.8% (4,451 km^2) of secondary vegetation, 21.7% (4,234 km^2) of pastureland, 5.6% (1,085 km^2) of area under agricultural activity and 1.8% (344.9 km^2) of deforested areas. Only 0.1% (23.9 km^2) was classified as urban area and 0.9% (167.2 km^2) as other land use classes (non-forested areas and hydrography) (**Fig. 4c**).

The confusion matrix used to compare category by category in relation to the reference data and the corresponding results of the automatic classification showed that general accuracy was 97.3%, a similar value to the Kappa index, which was 96.7%. Another way to analyse the confusion matrix would be through omission and commission errors. Omission errors were 1.3% (forest), in other words, three visited points that should have been classified as forest, were not. The following categories were: secondary vegetation (6.1%; six visited points), pastures (5.8%; 12 visited points), agriculture (4.4%; 10 visited points), and deforestation (1.2%; 10 visited points). There was no omission error for the hydrology category (**Table 1**).

Table 1. Confusing matrix of the unsupervised classification of satellite images - Landsat - 8 (08/08/2020) with their respective percentages of producer and consumer accuracy, commission and omission errors, general accuracy and Kappa indexes in the municipality of Paragominas, Brazilian Amazon.

	Reference samples						
Class	Forest	Hydrology	Secondary vegetation	Pasture	Agriculture	Deforestation	**Total**
Forest	147	0	2	0	0	0	149
Hydrology	0	425	0	0	0	0	425
Secondary vegetation	2	0	107	5	0	0	114
Pasture	1	0	3	242	7	4	257
Agriculture	0	0	1	6	281	6	294
Deforestation	0	0	0	1	3	213	316
Total	150	425	113	254	291	322	1,555
Producer’s accuracy %	98.0	100	94.7	95.3	96.6	96.9	
User’s accuracy %	98.7	100	93.9	94.1	95.6	98.7	
Commission error %	2.0	0.0	5.31	4.7	3.4	3.1	
Omission error %	1.34	0.0	6.1	5.8	4.4	1.3	
Overall accuracy %	97.3						
Kappa index %	96.7						

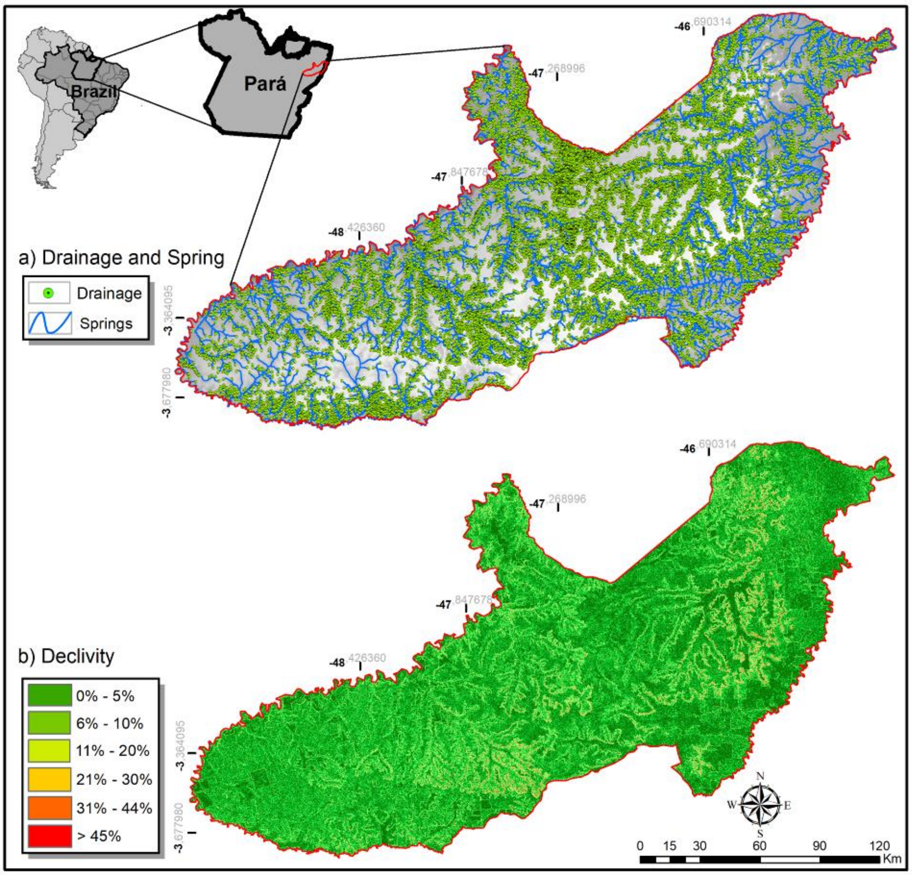
Commission errors show points that were wrongly included in another category. **Table 1** shows that 2.0% (two points) of the forest category were incorrectly included in the secondary vegetation category. For the following categories, there were: secondary vegetation 5.3% (two points classified as forest and five as pasture); pasture 11.1% (one point as forest, three points as secondary vegetation, seven points as agriculture and four points as deforestation); agriculture 3.4% (one point classified as secondary vegetation, six points as pasture and six points as deforestation); deforestation 3.1% (one point classified as pasture and three points as agriculture) and there was no commission error for the hydrology category (**Table 1**).

3.2 Identification of permanent preservation areas

Paragominas has a large hydrographic network, with 20,149 km of rivers and 15,824 springs mapped and 65% more drainage than in the official database of the National Water Agency (ANA), which informs 6,960 km of rivers in the municipality (**Fig. S4**; supplementary material). A total of 3,962 km of rivers and 5,269 springs were identified in livestock areas; 389 km of rivers and 741 springs in agriculture areas; 43 km of rivers and 122 springs in deforested areas; and 21 km of rivers and 25 springs in urban areas. The remaining vegetated areas totalled 15,737 km of rivers and 9,667 springs (**Fig. 5a**).

The average altitude in Paragominas' territory is 90 m, and most of the municipality is flat. In the classification for slope areas, only 0.1% (19 km^2) of the territory has a slope > 45º, which is considered a PPA according to the Brazilian Forest Code, while the rest of the municipality (99.9%; 19,446 km^2) has a slope < 45º (**Fig. 5b**).

Fig. 5. Classification and mapping of all permanent preservation areas (PPAs) in the municipality of Paragominas: a) rivers and springs; and b) slopes.



3.3 Environmental liabilities and the establishment of priority areas for restoration in rural properties

In **Figure 6**, we selected an example (a rural property) detailing the entire sequence of how priority areas for restoration were selected. The database of rural properties registered on CAR was used, where PPAs (rivers, springs and areas sloping more than 45º) and the classification of satellite imagery were identified. Approximately 94% of all rural properties (1,210) in Paragominas were properly registered on CAR, which sums up to 15,149.78 km^2 of the municipality's territory. From this total, 720 (14,747.34 km^2 of the total rural properties) had more than four fiscal modules, of which 273 (3,668.33 km^2 of the total rural properties) showed less than 50% of LR, with 239 (3,472.96 km^2) rural properties showing degraded PPAs, which are considered environmental liabilities that need to be recovered. We identified 182 (6,270.25 km^2) rural properties with more than 50% of LR required by law, but with degraded PPAs. Of the 490 (402.44 km^2) rural properties with fewer than four fiscal modules, which had no obligation to maintain LR, 105 (140.58 km^2) properties showed degradation in PPAs (**Fig. 7; Table 2**).

Table 2. Summary of data on environmental liabilities and the establishment of priority areas for restoration in rural properties in the municipality of Paragominas, Brazilian Amazon.

	> 4 Fiscal modules		< 4 Fiscal modules*		
	< 50% LR	> 50% LR	< 50% LR	> 50% LR	Total
Total area of rural properties (km^2)	3,668.33	11,079.01	267.04	135.40	15,149.78
Total forest of rural properties (km^2)	1,220.14	8,527.21	43.29	99.16	9,889.80
Total LR area of rural properties by law (km^2)	1,834.16	5,539.50	133.52	67.70	7,574.88
LR deficit - Environmental liabilities (km^2)	614.02	-2,987.71	90.23	-31.46	704.25**
Number of rural properties with degraded PPA	**239**	**182**	**85**	**20**	**526**
Number of rural properties	**273**	**447**	**330**	**160**	**1,210**

*No LR obligation.

Fig. 6. Details of the selection sequence of priority areas for restoration from the database of rural properties registered on CAR, areas of permanent preservation and classification of land use and coverage

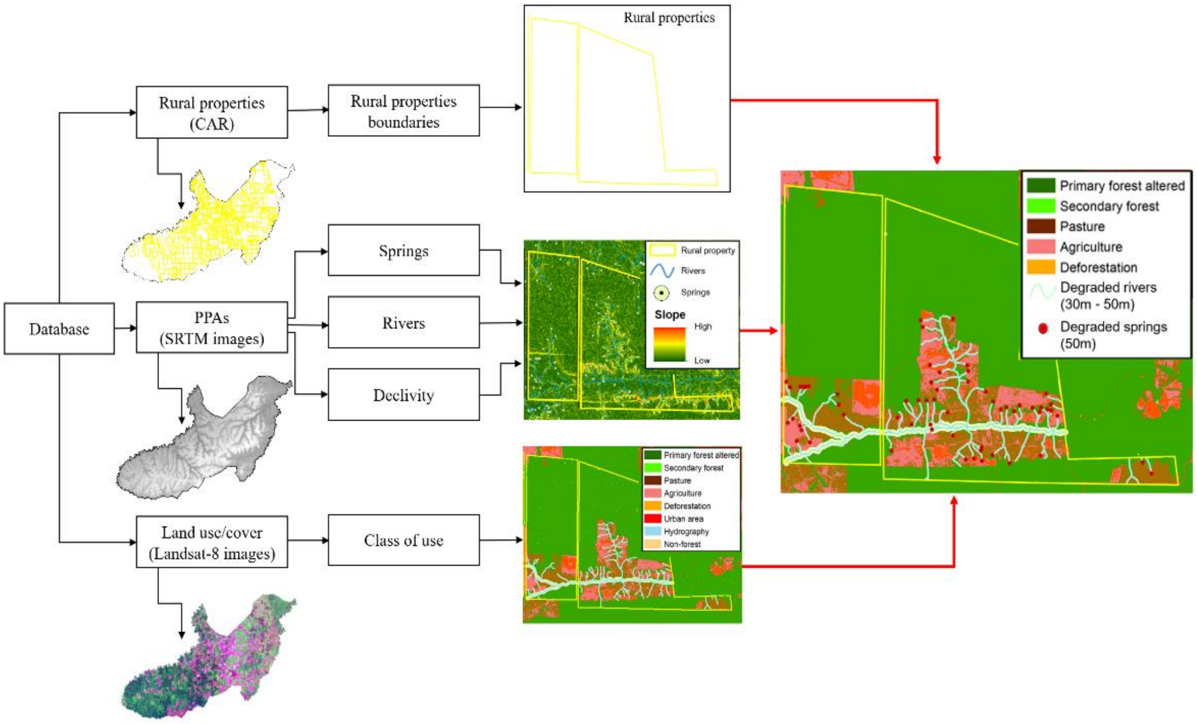
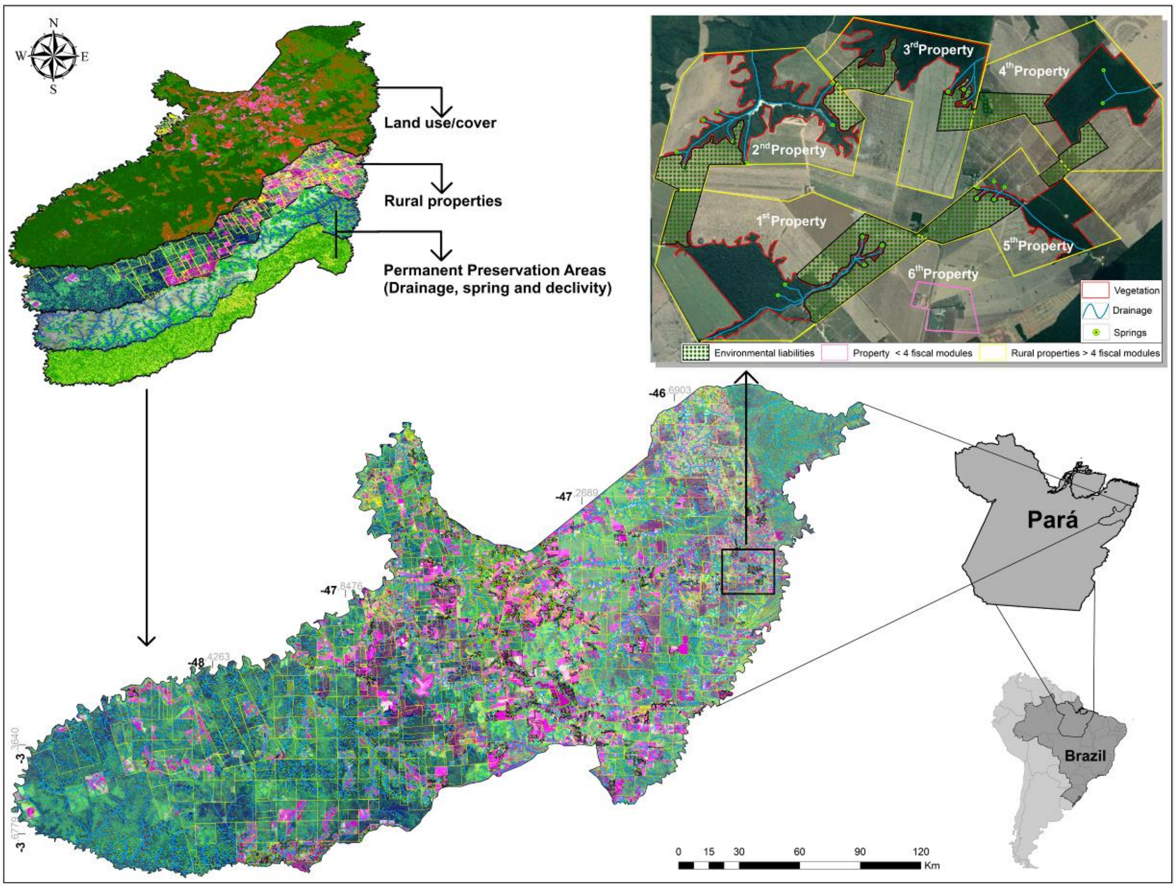


Fig. 7. Mapping of all environmental liabilities in the municipality of Paragominas, Brazilian Amazon, Brazilian Amazon, using the land use classification, the database of all rural properties and degraded permanent preservation areas (PPAs). The result was a map of the environmental liability that connects all vegetation zones between rural properties.



Based on all environmental liabilities of the properties analysed in this study, 614.02 km^2 of degraded areas were mapped within the rural properties in the municipality, which, due to legal obligation, should be forested. In the areas with environmental liabilities as part of the rural properties, there were 1,649 km of rivers and 2,238 springs of PPAs, distributed over 239 rural properties. On the other hand, 182 other rural areas with degraded PPAs were also identified in properties with more than 50% of LR (**Table 2**).

The PCA carried out in this study showed that most of the variables analysed presented a relevant degree of interaction in the selection of priority areas for forest restoration and establishment of ecological corridors. Using PCA, we identified that the first two principal components were responsible for 71.8% of the total variation in priority areas for restoration in rural properties (PC1 = 50.05% and PC2 = 21.75%). There was great similarity and correlation between the variables environmental liability, degraded rivers and degraded springs. They formed acute angles to each other, in addition to being longer and closer to the axis. However, there was an evident separation between the areas with the smallest and largest four fiscal modules. The scores of main component 1 (PCA-1) were positively correlated with environmental liabilities, degraded rivers, degraded springs and distance from liabilities to forest fragments. There is a significant change in the abundance of data, as shown in **Figure 8**, also correlated at the bottom of the graph with the deforestation and vegetation variables.

Fig. 8. Standardised variables present in rural properties with environmental liabilities in the municipality of Paragominas, Brazilian Amazon, through Principal Component Analysis (PCA). There is a correlation between the variables that make up the selection of priority areas for restoration and ecological corridors in the municipality

4. DISCUSSION

4.1 Landscape change over the last 36 years (1984 - 2020)

Environmental degradation has increased over the last few decades. In the Brazilian Amazon, the opening of roads, forest conversion into pasture and agriculture, timber and ore extraction and fires have historically been the main causes of forest loss and degradation since the 1970s. So far, this has resulted in 20% (788,353 km^2) of forest cover loss in the Brazilian Amazon (Solar et al., 2016; INPE, 2019; da Cruz et al., 2020a), a larger area than the Turkish territory. Of this total deforested area, ca. 34% (271,862 km^2) have taken place in Pará state, where Paragominas has had a significant contribution (8,817.7 km^2), mainly from lands converted to other uses, especially to agriculture, livestock and mining activities (INPE, 2019; Solar et al., 2016). The identification of these areas was corroborated by the confusion matrix, an accuracy estimation technique widely used in remote sensing analysis (Story & Congalton, 1986; Chuvieco, 1990; Congalton, 1991; Fidalgo, 1995; Lillesand et al., 2004: Congalton & Green, 2019). The overall accuracy of 94% and the Kappa index of 93% were excellent percentages according to the classification by Landis & Koch (1977).

Growth and economic dynamics in Paragominas were mostly originated by the federal development policies established in the 1970s (Mahar 1979; Hall 1991). These policies did not have clear sustainable criteria regarding the conservation of natural resources. This led to strong environmental degradation in Paragominas and, as a result, for many years, the municipality showed high deforestation rates.

According to the Brazilian Forest Code, there are directives and norms addressed to rural properties (Law no. 12,651/2012), so that their activities comply with legal requirements (CFB, 2012). However, the lack of supervision and inappropriate management in the environmental sector leads to illegalities that still persist nowadays. In the Brazilian Amazon, properties in municipalities with deforestation over the maximum allowed per year are unable to access the financial credits provided by the federal government. Furthermore, according to Decree no. 6321/2007, municipalities with excessive deforestation are included on a red list of the Ministry of Environment, and they are required to restore their degraded areas.

4.2 Forest restoration in permanent preservation areas (PPAs)

Studies have pointed out that the PPAs of rivers and springs show excellent possibilities for restoration purposes (Samia et al., 2015). They are areas of stability and biodiversity balance; they promote wildlife protection and provide efficient ecological corridors to connect fragmented areas (Clerici and Vogt, 2013; Fremier 2015). PPAs contribute to the genetic flow of plant and animal communities (Sutton et al., 2010), and they form good barriers against forest fires (Lovell 2006). However, it is not easy to determine the ideal width of a riparian zone that can maintain the ecosystem equilibrium (Sweeney, 2014), since the effectiveness of river PPA zones depends, among other factors, on climate, physiography, vegetation type and declivity (Valle et al., 2013).

The municipality of Paragominas has an extensive network of rivers and springs considered to be PPAs. Notwithstanding, many of these PPAs are found in areas under agricultural use and, depending on the quality of the management adopted, they are affected by contaminants in soil particles (Klapproth, 2009; Pires et al., 2009), which can pollute water bodies (Sutton et al., 2010).

Land use and occupation analyses associated with studies to understand the dynamics of water resources (morphometric analysis) are important to propose actions to preserve the hydrographic network. It can also help to control the erosion of rivers and sedimentation of water bodies. While these phenomena, erosion and sedimentation, occur naturally, they are also associated with unsustainable land use (Hughes et al., 2016). Pinto (2003) identified agricultural and livestock economic activities in PPAs, which are zones that must be legally protected. This situation has also been evidenced in this study.

The hydrographic network, with its watersheds and micro watersheds, shows adequate and unique conditions for environmental planning, land use management and nature conservation (Santos, 2015; Álvarez et al., 2017). Paragominas has two important watersheds: the *Capim* River watershed and the *Uraim* watershed. These watersheds make up important rivers in the municipality. The *Capim* River serves as the municipality’s natural boundary; and the *Uraim* River, a tributary of the *Gurupi* River, provides the water supply for the municipality. The large extension of rivers identified in this study showed producer and consumer accuracy of 100% and error 0, also proven in other studies (Kuo et al., 2001; Bolaños-González et al., 2001; Oliveira et al., 2009; Acharya et al., 2016). Our result is much larger than the official data of the National Water Agency (ANA), which has Ottobasin as elementary drainage units, also generated from a consistent digital hydrological elevation model (SRTM). SRTM is a classification technique widely applied to define the water network. It is advocated by many authors as the most used classification model, even assisting managers in making decisions about water resources (Galvão & Meneses, 2005; Gomes & Lobão, 2009; ANA, 2017).

Activities related to the preservation or recovery of watersheds promote the rational use of natural resources at national, state and municipal levels, according to identified needs and priorities (Souza et al., 2000). Some important roles played by watersheds include containing floods, absorbing the excess of nutrients, absorbing runoff water, providing better retention of sediments and agrochemicals from agricultural activities, providing organic matter for river food chains, protecting the flora and fauna in the system, reducing silting of rivers and increasing flow capacity during droughts (Zolghadr-Asli, 2017; Patil, 2020). Because of all these reasons, it is important to maintain the balance of such habitats for the benefit of society and the ecosystem as a whole.

4.3 Environmental liabilities, establishment of priority areas for restoration and creation of ecological corridors

Once established, CAR enables a better management of environmental actions in rural properties throughout the Brazilian territory. CAR produces a diagnosis of environmental compliance or non-compliance by property owners, providing a broad profile of the environmental status of rural properties to public authorities. This document makes it possible to identify the environmental liability of irregular properties (De Alcântara, 2014). On February 18th 2020, Paragominas had 94% (1.8 million ha) of its rural properties registered on CAR (available at: http://www.car.gov.br/publico/imoveis/index). A great potential for the recovery of degraded areas includes the LR areas and PPAs because they hold great diversity of plant species, which favours the natural recovery of adjacent areas (Moressi.2014).

Subsequently to the diagnosis, irregular rural properties in Brazil must design an Environmental Regulation Programme (abbreviated as PRA, in Portuguese), presenting a Recovery Project for Degraded and Altered Areas (abbreviated as PRADA, in Portuguese). Landowners are committed to maintaining and recovering native vegetation in PPAs and LRs or to compensating for their LR deficit through instruments such as environmental leases by acquiring native vegetation areas in the same biome as that of the penalised property (Zakia & Pinto, 2013). According to Brancalion et al., (2016), in order to ensure ecosystem and conservation services and maximise ecological benefits, LR compensation must occur as close as possible to the degraded area, preferably in the same watershed.

To select priority areas for restoration, some authors (Forman, 1997; Uezu et al., 2005) used the following criteria: degraded PPAs, vegetation fragments and the proximity between rural properties with environmental liabilities. This selection can increase forest connectivity through ecological corridors that, in addition to preventing species losses (Lopes et al., 2009), facilitate genetic flow between fauna and flora communities (Saura & Rubio, 2010; Beier et al., 2011; Singh & Gokhale, 2015; Perkl, 2016; Peng et al., 2017). For all these reasons, we suggest prioritizing the restoration of PPAs in LRs with environmental liabilities in rural properties in Paragominas. Nevertheless, it is necessary to take into account that the selection of a priority area for restoration depends on the restoration objectives. This can include multi-objective planning in which nature conservation and other issues (social and economic) must be involved (Kangas & Leskinen, 2005).

Environmental protection organisations recognise the importance of establishing ecological corridors on a large scale for maintaining the biodiversity and functional integrity of ecosystems (Bowers & Mcknight, 2012). The establishment of ecological corridors can increase persistence chances of plant and animal populations in isolated forest fragments (Pardini et al., 2010; Baranyi et al., 2011). Moreover, they play important roles in providing routes for migratory species (Aars & Ims, 2008) as they help with the function of forest connectivity and can significantly improve water quality in degraded PPAs (Valente & Vettorazzi, 2008; Pirnat & Hladnik, 2016; Mcdonald et al., 2016).

PCA showed that most of the variables analysed have an important degree of interaction in the selection of priority areas for forest restoration and the establishment of ecological corridors. PCA confirmed the effect of factors such as the distance from areas under environmental liabilities, degraded rivers and springs in the selection of priority areas for restoration, showing that these variables are correlated with degraded areas in rural properties. In a recent study, da Cruz, et al. (2020b) identified that the closer the zones in a succession of seed sources, the greater the richness and abundance of species in the municipality of Paragominas. According to Rencher (2002), at least 70% of the total variance must be explained by the first and the second principal components.

4.4 Current scenario – Advances and Obstacles

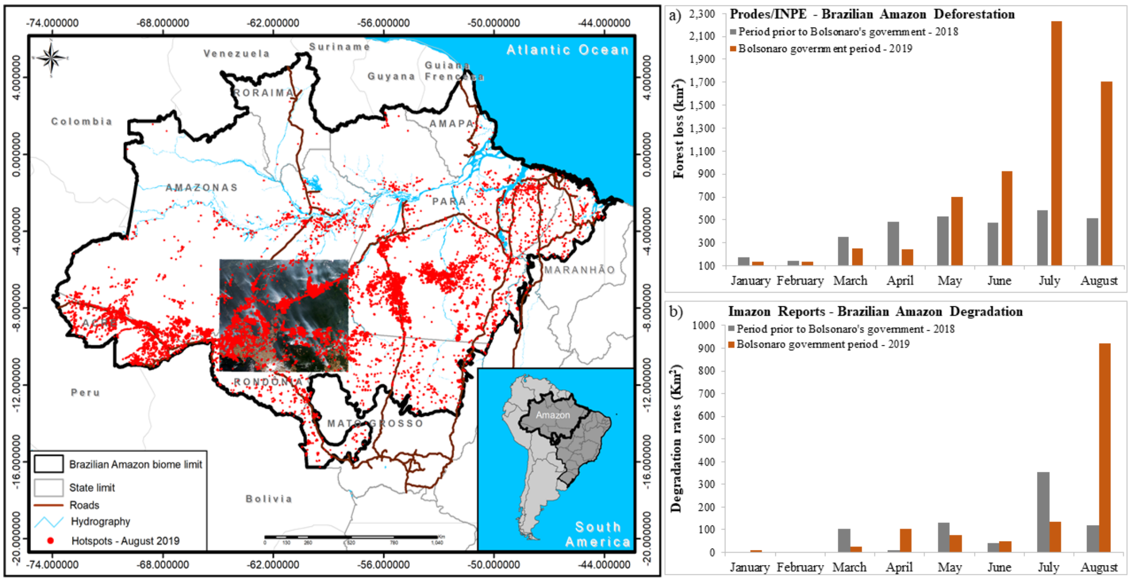
There are ca. 2 billion hectares of degraded land across the planet (Minnemeyer et al., 2011). Countries are increasingly debating the climate situation in the world, and in 2004, the

United Nations Climate Summit in New York established that it is necessary to restore 350 million ha (Latawiec et al., 2015). To fulfil its part of the agreement, Brazil has been taking legal measures and forest restoration actions, such as the creation of the National Plan for the Recovery of Native Vegetation – Planaveg (MMA, 2017). The Brazilian strategy created in 2017 aims to restore at least 12 million hectares by 2030, mainly in PPAs and LRs, as suggested by the present study.

Studies point out that Brazil has a deficit of 21 million hectares of PPAs and LRs in private properties (Soares-Filho et al. 2014) in addition to the legal barriers affecting conservation efforts to restore vegetation after the approval of the new Brazilian Forest Code (Law no. 12,727/2012). By introducing an “amnesty” to rural properties that had deforested until June 2008, it leads landowners to “understand” that they are exempt from the environmental liability. This scenario has led to a significant reduction in the requirement to recover PPAs and LRs in the country. It is estimated that 30 to 40 million hectares will not be recovered due to these circumstances (Brancalion et al., 2016; Guidotti et al., 2017). From 369 rural properties with environmental liabilities analysed in this study, only 79 were deforested after 2008, but in all of them, degradation in PPAs was identified, which, due to the Brazilian Forest Code, must be recovered. Furthermore, this law suspends fines on properties deforested before 2008, but does not exempt them from the obligation to recover previously degraded areas.

Restoration of millions of hectares and deforestation reduction to 80% by 2020 (Copenhagen Accord, 2009) are commitments by the Brazilian federal government. Nonetheless, Brazil is currently facing a political situation that does not enhance environmental protection and conservation. Such commitment seems to be an impossible goal considering the attitudes of the country’s current President Bolsonaro’s government. Since the beginning of his presidential term on January 1st, 2019, degradation and deforestation rates have increased (Escobar, 2019a). This rise has occurred mainly in the Amazon region, where there was a 75% increase in degradation from January to August 2019 (1,320 km^2) as compared with that in the same period in 2018 (755 km^2). August 2019 was the period of greatest degradation in the Amazon, exactly when there were numerous fires in the region. (**Fig. 9**; Escobar, 2019a). Despite the President’s claims that the Brazilian Amazon fires had climate changes as their cause (Artaxo, 2019; Escobar, 2019a, 2019b), up-to-date research shows that such events resulted from the recent weakening of law enforcement by the government, lack of monitoring and incentives for the country’s unsustainable economic development (Pereira, 2019; Vazquez, 2019; Escobar, 2019b, Artaxo, 2019).

Fig. 9. Brazilian Amazon map, with data on the hotspots of the month of August 2019 (Source: Own design based on the Inpe/dgi/fires database (http://queimadas.dgi.inpe.br/queimadas/bdqueimadas/), representing the region’s situation in relation to the increased number of fires in the period. Next to the map is NASA’s image (Landsat/MODIS sensor) illustrating the fire intensity seen by satellite images and a graph quantifying the increase in forest degradation from January to August 2019 (Source: Own design based on data from reports by the Deforestation Alert System - SAD, from the Institute of People and the Environment of the Amazon - IMAZON: https://imazon.org.br/).



5. CONCLUSION

Paragominas, due to its history of rapid economic growth and exploitation of natural resources in a short period of 36 years, has almost half of its territory deforested and mainly converted into agriculture and livestock land uses. This study has identified deforestation and degradation in zones that should be vegetated, the permanent preservation areas (PPAs). Proposing priority areas to restore degraded environments is a complex process in the Brazilian Amazon; however, in this study, important factors have been considered in terms of decision making, such as the identification of deforested areas and vegetation within rural properties and degraded PPAs.

With the mapping of the evaluated variables, it was possible to examine the data concerning the rural properties in order to suggest areas to be recovered and create ecological corridors to connect remnant forest fragments still present in Paragominas' territory and thus reduce the municipality's environmental liabilities. This method and our research results can also be applied to other municipalities or biomes to diagnose the situation of PPAs and propose more precise actions.

Current Brazilian environmental laws, especially the Brazilian Forest Code, have guidelines and standards to be applied in rural properties. Therefore, rural properties' activities must be in accordance with legal requirements, respecting the natural limits of the environment. However, the lack of law enforcement and loose management of economic activities allow illegalities to persist.

Forests and other natural plant formations play an essential role in the maintenance of the planet's large environmental processes, such as water cycles, climate regulation and maintenance of soil nutrients. When rural landowners protect slopes, springs, and watercourses, they are not only helping to conserve PPAs, but they are also helping to maintain the water resources that benefit the entire ecosystem. Once rural landowners preserve and maintain their properties' PPAs, they contribute to the maintenance of ecosystem services, such as higher biodiversity, the balance of carbon, water and soil emissions, which are of local, national, and global interest.

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7. SUPPLEMENTARY MATERIAL

Figure S 1. Samples collected in the satellite image - confusion matrix

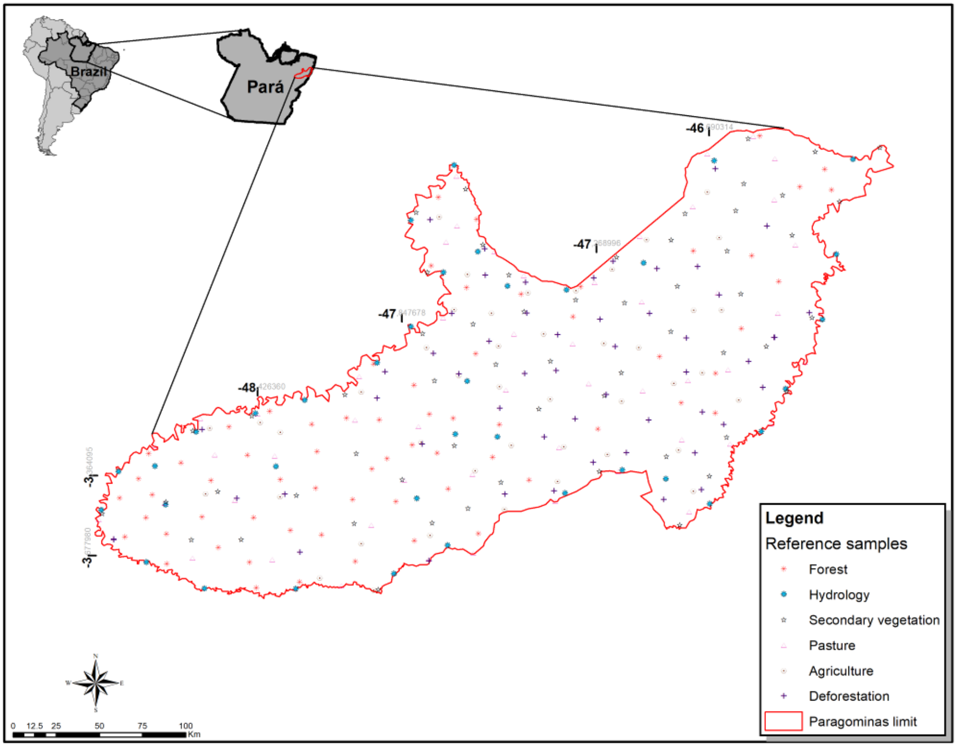


Figure S 2. Vegetation along water courses, with a buffer zone

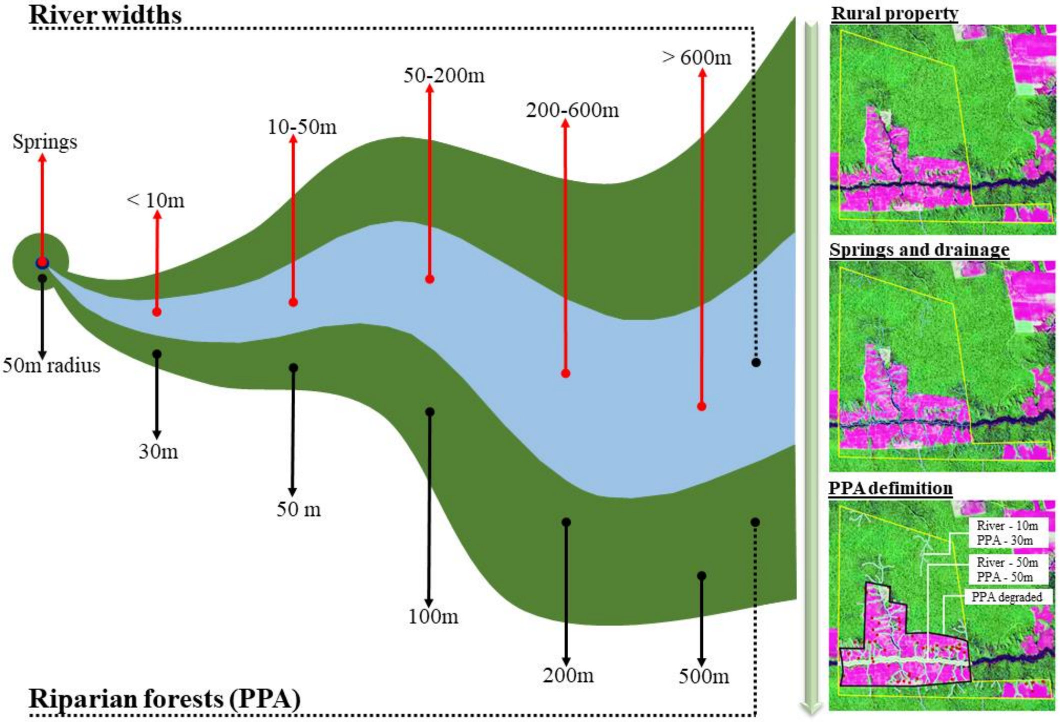


Figure S 3. Methodological procedures for identification and elimination of overlaps between the polygons of rural properties

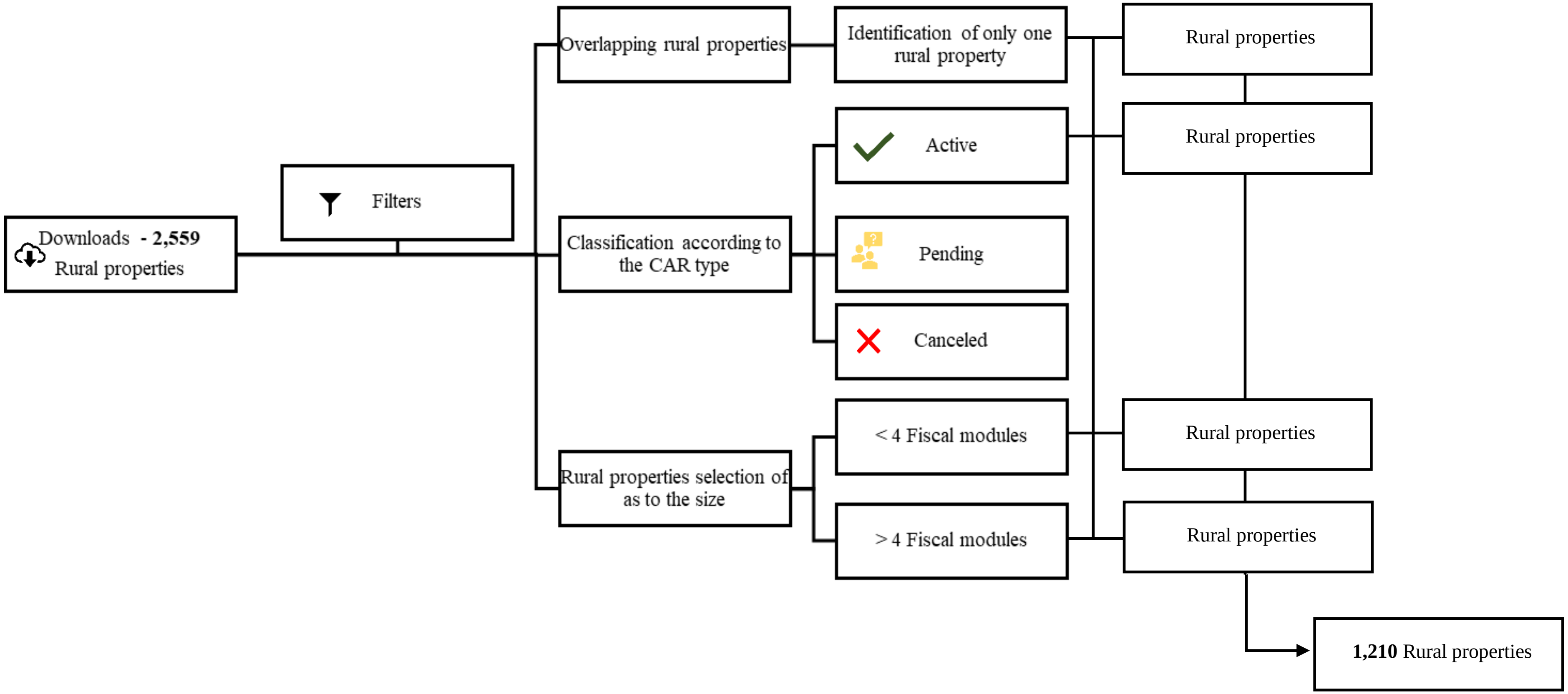
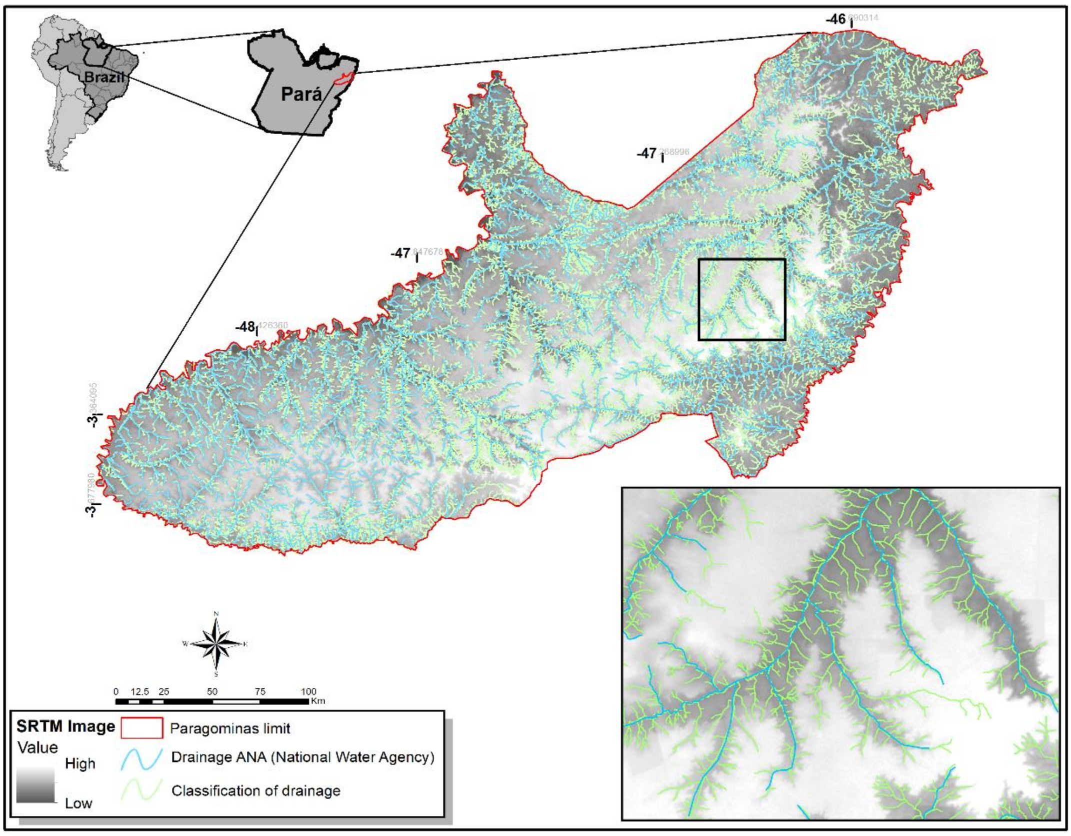


Figure S 4. Hydrographic network (National Water Agency and classification SRTM



CAPÍTULO III: RESTORATION THROUGH TRENCHES AFTER KAOLIN MINING: EFFECTS OF ORGANIC FERTILIZATION ON PLANT DEVELOPMENT.

Artigo submetido na revista New Forests

Abstract

Mining has continued to expand in the Brazilian Amazon since the time of the major projects that began in the 1970s. In such scenario, the Pará state plays an internationally prominent role. This situation has caused severe damage to the environment over the years, which has resulted in the current need to implement and improve methods for restoration of the areas degraded by mining. This study aimed to evaluate the growth of six forest species planted in trenches and submitted to three different types of organic fertilization: *i*) Topsoil; *ii*) Sawdust and *iii*) Cow manure. The trenches were opened with 1 m in width and 1 m depth by 40 m in length and were filled with topsoil. Between the rows (distance of 6 m between trenches), two treatments were performed: a) Covering with a 10-cm layer of sawdust in half of the experiment area and b) Without sawdust covering in the other half. The following variables were evaluated: (1) Mean Annual Increment in height (MAI_H); (2) Mean Annual Increment in diameter (MAI_{DSH}); (3) Mean Annual Increment in crown area (MAI_{CA}); (4) Percentage of soil occupation by non-tree and non-shrub species; (5) Natural regeneration density of tree species; (6) Survival of planted individuals and (7) Litter stock. The planted species *Clitoria fairchildiana*, *Tachigali vulgaris* and *Croton matourensis* showed the highest MAI_H and MAI_{DSH}, and the *Clitoria fairchildiana* species showed the highest MAI_{CA}. The addition of cow manure and sawdust did not result in better performance among the planted species. Herbaceous plants and grasses showed the highest mean percentage of soil occupation for all treatments (37.17%), and in the *Topsoil* treatment, 75% of the area showed exposed soil, exactly where there was the highest mortality rate (3.6%) of planted individuals. The density of individuals in natural regeneration and the litter stock were not influenced by the presence of sawdust between the rows. Despite the short time of the experiment implementation, the results showed great efficiency in the use of trenches for the restoration of areas degraded by kaolin mining.

Keywords: Forest restoration; soil reconstruction; selection of tree species; mining.

1. Introduction

Mining generates wealth for countries and drives economic development in the regions where its ventures are concentrated. On the other hand, this is an activity that results in severe environmental impacts, which requires a consistent recovery plan for the rehabilitation and/or restoration of degraded ecosystems (Gastauer et al. 2018). In forest restoration, priority is given to the return of ecosystem services, such as carbon sequestration, biogeochemical cycling and pollination, restoring the ecological functionality of the ecosystem (Hendrychová and Kabrna 2016; Hou et al. 2018). In addition, restoration actions must take cost-efficiency into account with the adoption of cheaper and more efficient alternative techniques (Crouzeilles et al. 2019).

Studies and experiments carried out for the restoration of post-mined environments have advanced rapidly in recent years (Martins et al. 2020b); however, results are not always successful when the objective is to recreate ecosystems (Wortley et al. 2013). A relevant factor is the diversified use of tree species in post-mining sites, as it favors a variety of habitats, naturally creating ecological niches that provide an increase in organism diversity (Wozniak et al. 2015; Kałucka and Jagodziński 2016; Gastauer et al. 2018). Such diversity ensures greater resistance and resilience of the forest ecosystem to possible attacks by pests and other degrading actions (Davis et al. 2012). Likewise, the status and effects of the fauna and microorganisms must be considered (Cristescu et al. 2012). Therefore, the restoration of the basic elements of the landscape, especially the fauna and flora, are priorities, since vegetation formation is essential for biomass composition (Mueller et al. 2016), stimulates biotic interactions and promotes the internal control of ecosystem processes (Lei et al. 2016).

Among the usual methods for restoring mined ecosystems is planting seedlings of different tree species (Martins et al. 2020b). This is an active restoration method that ensures greater initial plant density and diversity at the site, especially where resilience capacity is low and requires decades for revegetation to occur naturally. An example of this is that of the Atlantic Heathland, in southwestern England, where edaphic and vegetation characteristics in kaolin exploration areas have not been restored over a period of 150 years (Lane et al. 2020).

Despite the importance of diversified planting for forest restoration, some obstacles are evident, such as obtaining seeds and seedlings and the high mortality rate in initial plantings (Löf et al. 2019; Erickson and Halford 2020), which causes failures or small clearings that expose the soil to erosive processes and compromise the performance of other species, thus making the restoration project more expensive. For this reason, it is preferable to select species that are adapted to bioedaphoclimatic conditions, show rapid growth, facilitate recolonization by non-tree species and are, at the same time, attractive to wild fauna (Brancalion and Holl, 2020). Rustic and aggressive species that are capable of developing in hostile environments are indicated, as they contribute to rebalance and stabilize the ecosystem by acting on the natural mechanisms and processes of colonization (Ramos et al. 2020).

Monitoring the performance of the species included in the initial planting by means of structural indicators makes it possible to identify which species have the best performance in face of the applied methodologies (Martins et al. 2020b). Of the structural indicators, the measurement of dendrometric variables over time is easy to perform and interpret, making it possible to calculate the increment and thus assess the status of each species at the site being restored. However, the availability and distribution of resources among species with different ecological characteristics of succession respond naturally according to their physiological characteristics and specific growth rates (Macdonald et al. 2015). In this process, litter deposition is an important indicator to be considered, as it is through it that the transfer of nutrients to the soil, such as that of nitrogen, calcium, magnesium, and the partial dispersion of carbon dioxide occur, which enables fertility and local productivity (Diniz et al. 2015). In addition, litter helps with soil erosion control and protection (Józefowska et al. 2017), the regulation of surface hydrological processes and the germination of the seed bank (Quideau et al. 2013; Martins et al. 2018).

In view of the need to evaluate many indicators together, monitoring the restoration process is important to support the assessment of the recovery trajectory, which requires the use of meaningful and easy to interpret metrics (Wortley et al. 2013; Hou et al. 2018). Among these metrics are the abundance and richness of species (Bauman et al. 2015; Li et al. 2017; Shackelford et al. 2018), litter production and plant growth. Through the assessment of vegetation development, it becomes possible to know and understand the dynamics of ecosystems, to which the decomposition and cycling of nutrients are connected, as they are essential for post-mining forest restoration (Grant et al. 2007). In order to help tree development, the use of agricultural correctives and fertilizers is necessary in forest restoration procedures, and opting for organic fertilizers is a satisfactory alternative due to their efficiency and to the fact that resources available in the municipality can be used, since waste disposal, such as that of sawdust and cattle manure, is sometimes a problem. However, it is necessary to answer the key question in this context: Is the development of plants influenced by different types of organic fertilization, taking into account the development of trees? (H) Cow manure is expected to be a good option in favoring tree development. Therefore, this study aimed to evaluate the growth and mortality of tree species for the initial planting in trenches submitted to different organic fertilizers, as well as the development of natural regeneration in areas under restoration after kaolin mining in the Eastern Amazon.

1. Material and Methods

1.1. Study area

The study was conducted in an area belonging to Pará Pigmentos S.A. (PPSA), which is a mining company owned by the French company Imerys, located in the municipality of Ipixuna do Pará, Pará state, Brazil (**Fig.. 1**). The area, known as “Cota 85”, went through the mining process in 2013. Soil reconstruction took place between the end of 2015 and the beginning of 2016. The area was chosen for the installation of the experiment because of its characteristics that portray most of the post-kaolin mining environments in the Amazon, with unstructured soil horizons and high compaction.

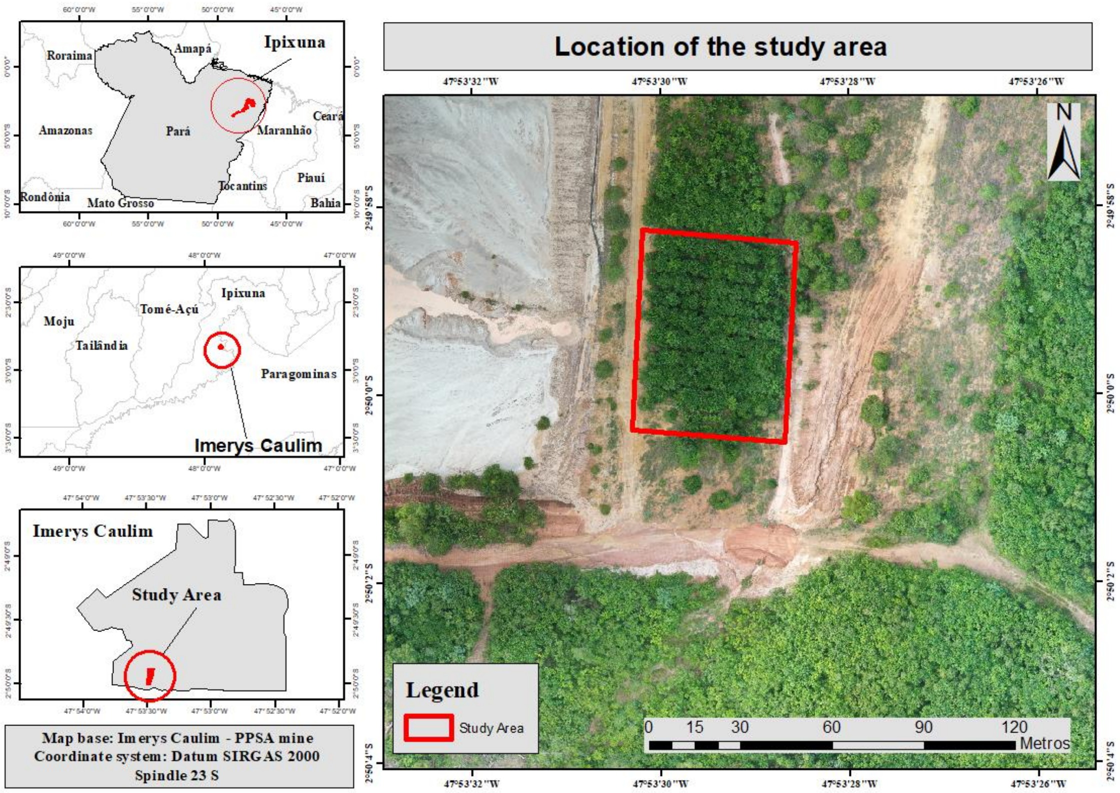


Fig. 1. Location of the study area (Pará Pigmentos S.A. mine), municipality of Ipixuna do Pará, Pará state, Brazil, under restoration after kaolin mining

According to Koppen's classification, the region's climate is the Am type, wet equatorial, with a moderate dry season from June to November (Alvares et al. 2014), mean annual rainfall of 1,750 - 2,500 mm (Andrade et al. 2017) and average temperature of 26.7 °C. The predominant vegetation is the lowland dense ombrophilous forest (IBGE, 2004). Near the experiment, on the south side, there are traces of primary vegetation and, on the east, traces of secondary vegetation (**Fig. 1**). The soils are well drained, thick and leached, with low natural fertility and a predominance of yellow dystrophic latosols (João et al. 2013).

1.2. Experimental design

The experiment was implemented in an area of 0.35 ha in November 2017. In that area, nine trenches measuring 1 m in width, 1 m in depth and 40 m in length were opened and filled with topsoil from the mined areas. The trenches were 6 m apart from each other.

Once the trenches were filled with topsoil, pits measuring 0.40 m x 0.40 m x 0.40 m (0.064 m^3) were opened, 1.5 m apart from each other, along the length of the trenches. Then 400 g pit^{-1} of simple superphosphate, 130 g pit^{-1} of urea and 130 g pit^{-1} of potassium chloride (KCl) were applied, divided into two applications with a 60-day interval. Next, three different organic compounds were added to the pits, in three treatments: *i)* topsoil, *ii*) sawdust and *iii*) cow manure. Each pit was filled with one of these three compounds (**Tab. 1**).

Tab. 1. Organic fertilization treatments applied for the restoration of a degraded area after kaolin mining. PPSA mine, Eastern Amazon, Brazil

Treatment	Description	Location	Pit preparation
Topsoil	Topsoil (Control)	Planting Row	-
Sawdust	Topsoil + Sawdust	Planting Row	40 liters of sawdust and topsoil.
Manure	Topsoil + Cow manure	Planting Row	40 liters of cow manure and topsoil.
Covered	Sawdust	Between Rows	-
Uncovered	Without sawdust	Between Rows	-

Between the trenches (between rows), two treatments were established: (a) addition of 10 cm of sawdust as a soil cover and (b) without sawdust addition. Each treatment occupied 50% of the total area between the rows (**Fig.. 2**). The disposed sawdust was composed of residues from sawmills near the PPSA mine, in the municipality of Ipixuna do Pará.

Fig.. 2. Simulation of the experimental area with 18 months of implementation and the distribution of topsoil, sawdust and manure treatments, where 50% of the area was covered with sawdust in forest restoration areas after kaolin mining, PPSA mine, Eastern Amazon, Brazil

From the establishment of the experimental treatments with Topsoil, Manure and Sawdust, 250 individuals of six species were planted, distributed among the three treatments (**Tab. 2**). Each planted seedling was marked with aluminum plates in order to make monitoring easier. The disposition of the species in the trenches (planting rows) was random, allowing, at most, the repetition of two individuals of the same species consecutively. The choice of tree species was made according to: *i*) ecological group; *ii*) rapid growth; *iii*) high survival; *iv*) N fixation in the soil; and *v*) litter production. The seedlings were produced in the company's own nursery six months before planting with seeds collected from native forests around the mine and conservation areas under the company's responsibility.

Tab. 2. Species and number of individuals per treatment, planted in the experiment to restore a degraded area after kaolin mining, PPSA mine, Eastern Amazon, Brazil

Species	***Topsoil***	**Sawdust**	**Manure**	**Total**
	Number of plants			
Byrsonima spicata (Cav.) DC.	14	14	14	42
Clitoria fairchildiana R.A. Howard	13	15	13	41
Croton matourensis Aubl.	14	14	14	42
Inga edulis Mart.	14	14	14	42
Syzygium cumini (L.) Skeels	14	13	15	42
Tachigali vulgaris L.F. Gomes da Silva & H.C. Lima	14	14	13	41
Total number of seedlings	**83**	**84**	**83**	**209**

Eighteen months after the implementation of the experiment, 48 plots measuring 2 m x 2 m (4 m^2) each were installed and randomly distributed over the entire experimental area in order to assess the density of the regenerating tree and shrub species. The soil vegetation cover percentage was also measured, and the vegetation was classified, according to its life form, as: *i*) herbaceous plants, *ii*) grasses and *iii*) lianas.

1.3. Variables analyzed

1.3.1. Vegetation

For the planted and naturally regenerated tree and shrub species, the following variables were measured: *i*) species identification (common and scientific names); *ii*) height (H); *iii*) diameter at soil height (DSH) and *iv*) canopy projection area for all planted individuals (Eq. 1). The mean annual increment (MAI) was calculated for the diameter, height and crown area (Eq. 2, 3 and 4). In addition, the survival percentage for the planted individuals was determined (Eq. 5).

$$\mathrm{Ac} = \pi \times \left[\frac{(\mathrm{L}_1 + \mathrm{L}_2)}{4}\right]^2 \qquad \text{Eq. 1}$$

$$\mathrm{IMA}_{\mathrm{DAS}} = \frac{\mathrm{DAS}}{\mathrm{T}} \qquad \text{Eq. 2}$$

$$IMA_{Ht} = \frac{Ht}{T} \qquad Eq.3$$

$$IMA_{Ac} = \frac{Ac}{T} \qquad Eq.4$$

$$S_{\%} = (N_1/N_i) \times 100 \qquad Eq.5$$

Where: C_A = Crown area (m^2); L_1 = Length of the longest longitudinal line of the crown (m); L_2 = Length of the perpendicular line to the longest longitudinal line of the crown (m); MAI = Mean Annual Increment (cm); DSH = Diameter at Soil Height (cm); T = Time (years); H = Height (m); S% = Survival Percentage; N_1 = Number of Living Plants; and Ni = Total number of planted seedlings.

The absolute density (AD) of the naturally regenerating trees was calculated by the ratio of the number of individuals by the area in which they were sampled (Eq. 6), whereas the soil cover rate assessment was made through the percentage occupied by herbaceous plants, grasses, lianas and the exposed soil.

$$DA = \left(\frac{N}{A}\right) \qquad Eq.6$$

Where: N = Absolute number of individuals of a determined species; and A = Sampled area (hectare).

1.3.2. Litter stock

For litter stock quantification, a template measuring 0.25 m x 0.25 m and 0.10 m in height was used. Samples were collected in the center of all the plots used to assess natural regeneration, totaling 48 samples, 24 in the planting rows and 24 between the rows. After collection, the samples were sent to the soil laboratory of the Federal Rural University of the Amazon, where they were dried at 60 °C until constant mass was achieved and were then weighed on an analytical balance (0.01 g). The scientific names of the regenerating species were verified on the Reflora database (http://floradobrasil.jbrj.gov.br/), and the APG IV classification system was adopted.

1.4. Statistical analysis

The experiment had a 6 x 3 completely randomized factorial design, with three replications and analysis of the performance of the six species in the three fertilization types in the pits. For MAI (height, diameter and crown area), litter stock and density of tree and shrub individuals, normality analysis was performed using the Shapiro-Wilk test (p-value > 0.05) and Levene's homoscedasticity test (p-value > 0.05). For the variables that did not meet the abovementioned assumptions, transformation was performed by Box-Cox, which indicated the best transformation type and, in some cases, outliers were excluded. Subsequently, analysis of variance (ANOVA) was applied. In case ANOVA showed significant difference, the means of the variables in the three fertilization treatments in the pit were compared using Tukey's test (p-value < 0.05) and Student's t test (p-value < 0.05) in order to compare the litter stock between the rows with and without sawdust spreading. Statistical analyses and graphical representations were performed using the R software, version 4.0.1 (R Core Team 2020).

2. Results

2.1. Increment of planted species

As for the mean annual increment in height (MAI_H), there was a significant difference between the treatments applied in the pits and between the species (**Fig. 3**). Topsoil showed the highest MAI_H (2.19 ± 0.60 m year^{-1}), but it did not differ from the sawdust treatment. Regarding the species, *Tachigali vulgaris* and *Clitoria fairchildiana* showed the highest MAI_H values, with 2.86 ± 0.19 and 2.61 ± 0.37 m year^{-1}, respectively (**Fig.. 3f and 3b**), not differing statistically from each other.

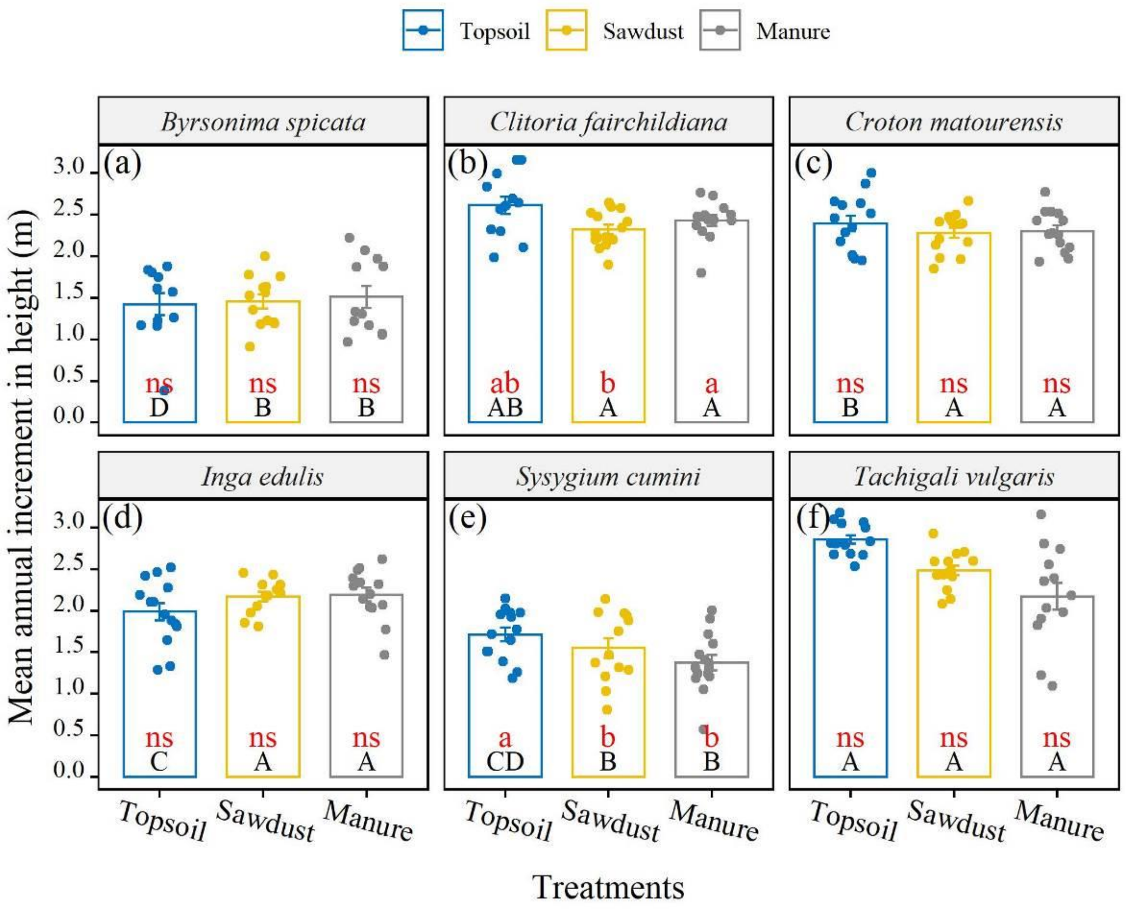


Fig.. 3. Mean (±SE) of the Mean Annual Increment in height (MAIH) for the six species planted in an area under restoration after kaolin mining, PPSA mine, Eastern Amazon, Brazil. Capital letters indicate differences between species for the same type of treatment with organic fertilization, whereas lower-case letters indicate differences between treatments with organic fertilization for the same species, according to Tukey's test (*p*-value ≥ 0.05). ns = non-significant difference, and each dot represents a plant of the respective species

For the mean annual increment in diameter at soil height (MAI_{DSH}), there was a significant difference between species ($F_{5;226}$ = 139.78; *p*-value < 0.001) and species interaction with different treatments ($F_{10;226}$ = 4.20; *p*-value < 0.001). However, unlike MAI_H, the treatments alone did not have a significant effect ($F_{2;226}$ = 4.20; p-value = 0.076). The highest mean IMA_{DSH} value was observed for *C. fairchildiana*, especially when it was submitted to the application of only *topsoil* or manure (**Fig. 4b**). Contrarily, the lowest mean MAI_H and IMA_{DSH} values, 50.35% and 73.80%, respectively, were observed for *Byrsonima spicata* (**Fig.. 4a).**

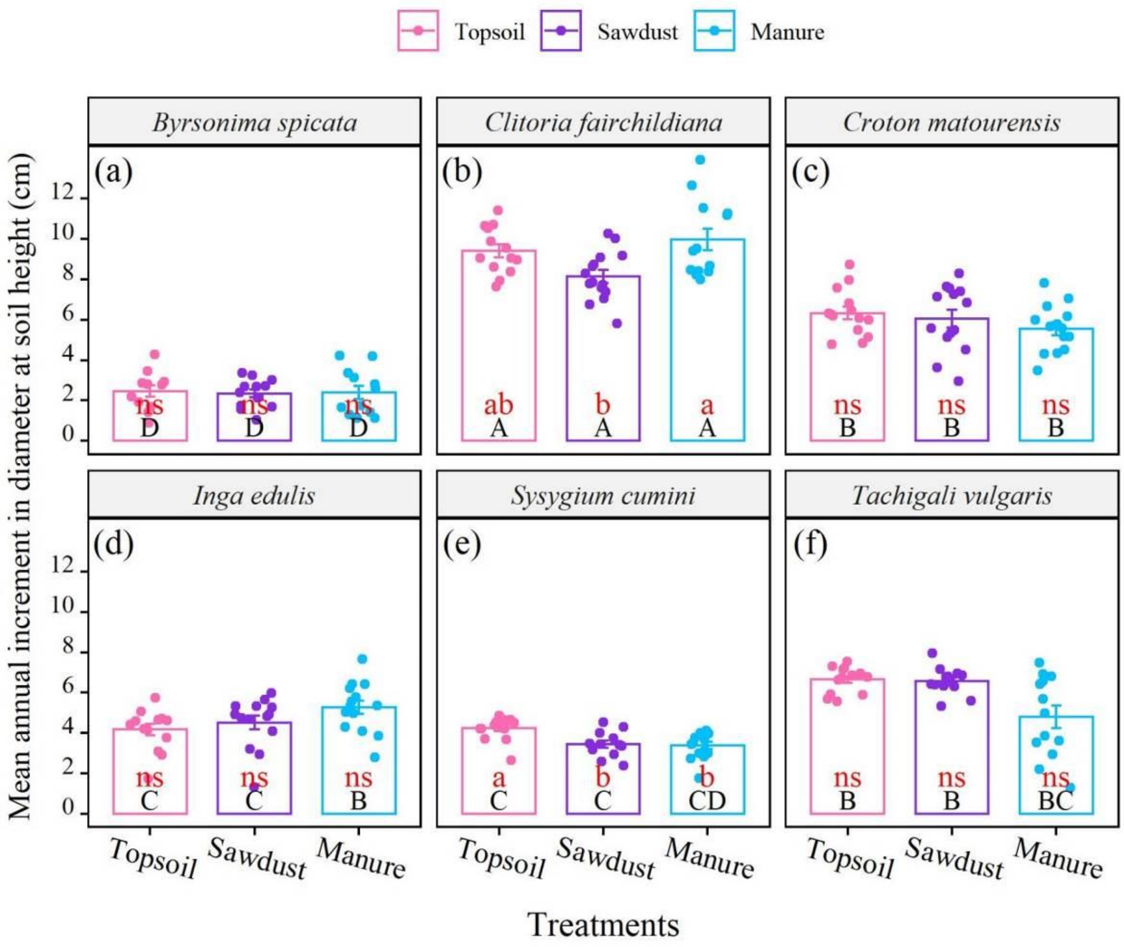


Fig.. 4. Mean (±SE) of the Mean Annual Increment in diameter at soil height (MAIDSH) for the six species planted in an area under restoration after kaolin mining, PPSA mine, Eastern Amazon, Brazil. Capital letters indicate differences between species for the same type of treatment with organic fertilization, whereas lower-case letters indicate differences between treatments with organic fertilization for the same species, according to Tukey's test (*p*-value ≥ 0.05). ns = non-significant difference, and each dot represents a plant of the respective species

The total area occupied by the crowns of all individuals planted was of 0.30 hectares, representing 85.71% of the whole experimental area. Of this percentage, the Topsoil treatment contributed with 31.98%, and Sawdust with 30.37%. The mean annual increment in crown area (MAICA) differed statistically between species (F5;226 = 100.34; p-value < 0.001), between treatments (F2;226 = 8.58; p-value < 0.001) and between the interaction of the two factors (F2;226 = 2.57; p-value = 0.006). The application of Topsoil alone was the best treatment, and it did not differ from Sawdust (p-value = 0.330). For C. fairchildiana, the highest mean MAICA was observed (Fig. 5b), whereas B. spicata and Sysygium cumini showed the lowest values (Fig. 5a). The Croton matourensis, Inga edulis and Tachigali vulgaris species showed statistically equal mean MAICA values between each other (**Fig.. 5c, 5d and 5f**). Finally, in 18 months, the survival rate was 97.6% throughout the experiment, which represents the mortality of six B. spicata individuals, of which four were under the Topsoil treatment, and two were under the Manure treatment.

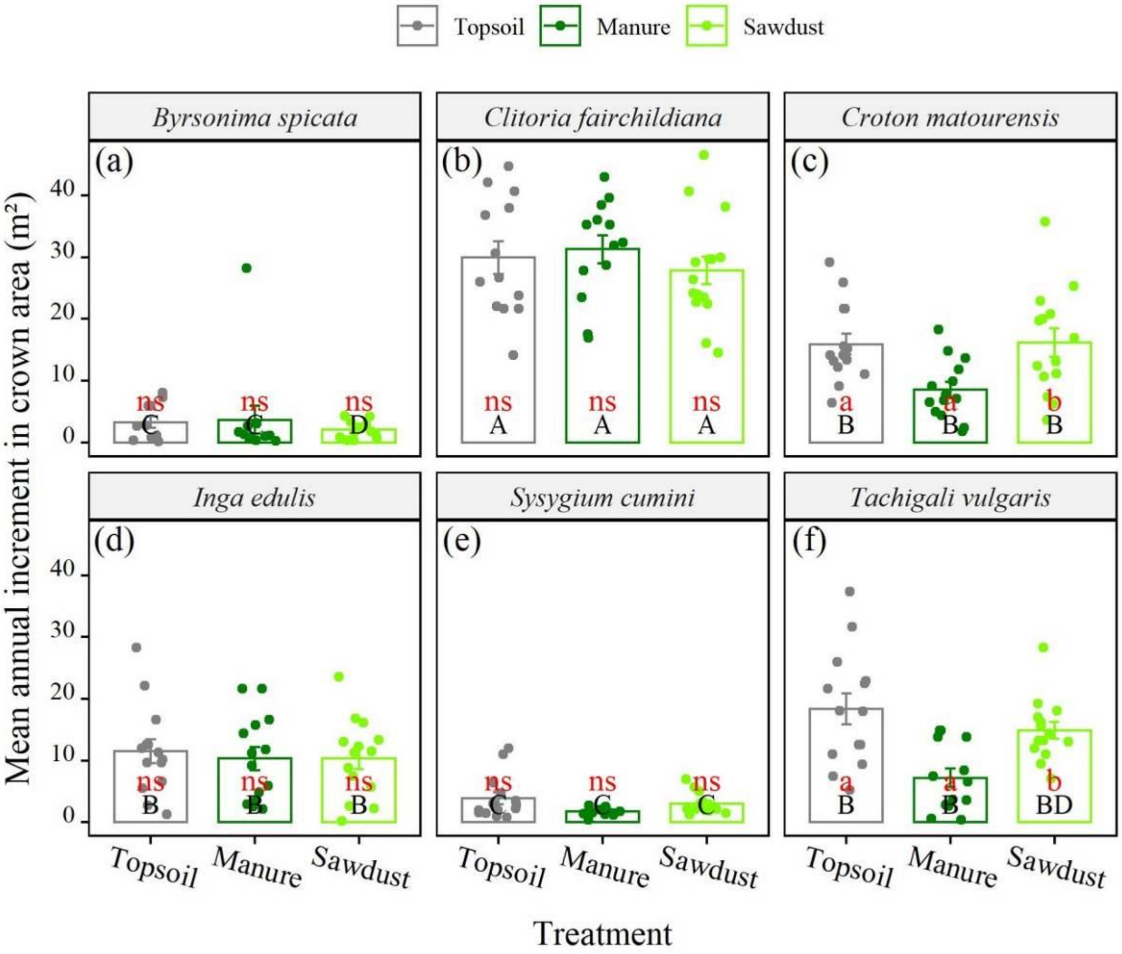


Fig.. 5. Mean (±SE) of the Mean Annual Increment in crown area (MAICA) for the letters indicate differences between species for the same type of treatment with organic fertilization, whereas lower-case letters indicate differences between treatments with organic fertilization for the same species according to Tukey's test (*p*-value ≥ 0.05). ns = non-significant difference, and each dot represents a plant of the respective speciessix species planted in an area under restoration after kaolin mining, PPSA mine, Eastern Amazon. Capital

2.2. Natural Regeneration Assessment

The percentage of soil cover by natural regeneration was less than 50% of the total area, with a predominance of herbaceous plants, grasses and lianas (Fig. 6). Among the life forms, lianas predominated, followed by grasses (**Fig.. 6**). Among the treatments, Topsoil showed 73% of exposed soil, whereas, of the 27% of covered soil, the Sawdust and Manure treatments showed higher coverage percentages, namely, 60% and 55%, respectively.

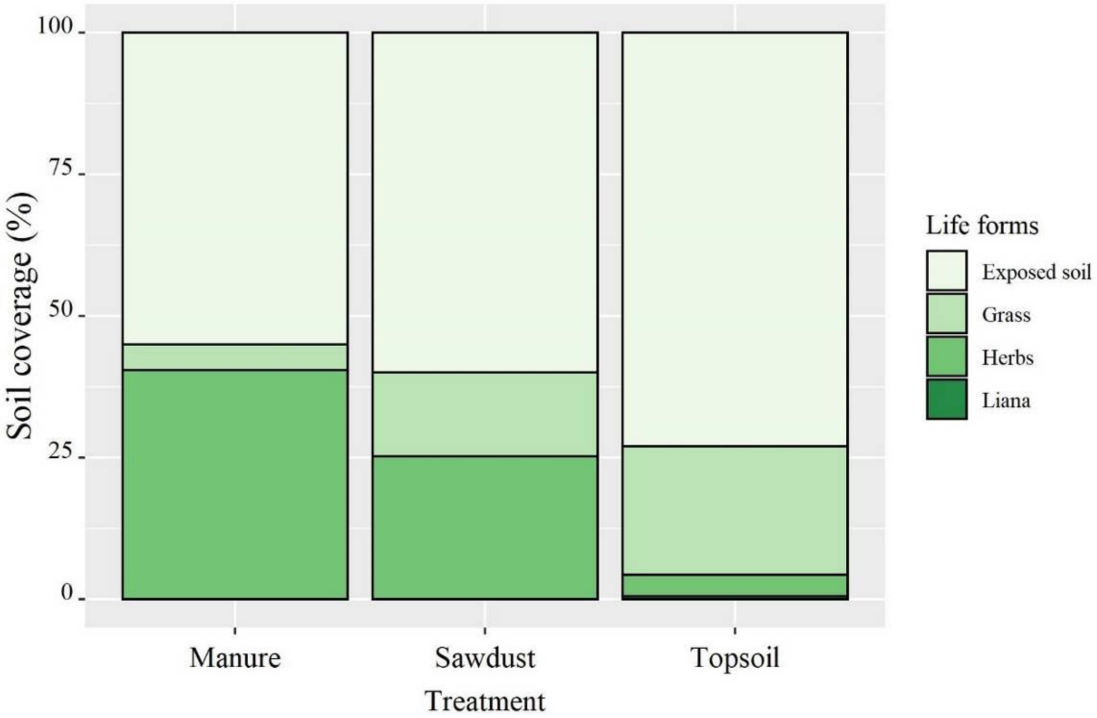


Fig.. 6. Cover percentage for the soil occupied by the herbaceous, grass and liana file forms in three organic fertilization treatments in an area under restoration after kaolin mining, PPSA mine, Eastern Amazon, Brazil

The regeneration of tree species between the rows was numerically greater in the Uncovered area, but it did not statistically differ from that in the Covered area ($t = 0.73$; *p*-value = 0.473). Species richness was low, with lower values in the Covered treatment and with only three species being recorded. Of such species, 520.83 *Acacia mangium* individuals ha^{-1} were found, which represents 40% of the density of individuals recorded for this treatment (**Tab. 3**).

Tab. 3. Density of regenerating tree and shrub species in an area under restoration after kaolin mining with (covered) and without (uncovered) the cover of a 10-cm sawdust layer, PPSA mine, Eastern Amazon, Brazil

Species	**Density (Number of Individuals ha^{-1})**			
	Life Form	**Covered**	**Uncovered**	**Total**
Acacia mangium	Tree	520.83	1,041.67	1,562.50
Cecropia palmata	Tree	0.00	208.33	208.33
Lecythis pisonis	Tree	0.00	104.17	104.17
Solanum crinitum	Shrub	833.33	625.00	1,458.33
Solanum fulvidum	Shrub	104.17	416.67	520.83
Vismia guianensis	Tree	0.00	104.17	104.17
General		1,458.33	2,500.00	3,958.33

2.3. Litter Stock

The litter stock was not altered by the addition of sawdust (Covered) between the rows (t = 0.68; p-value = 0.421), nor between the treatments of the planting rows (Uncovered) (F2;18 = 2.29; p-value = 0.130) (**Fig.. 7**).

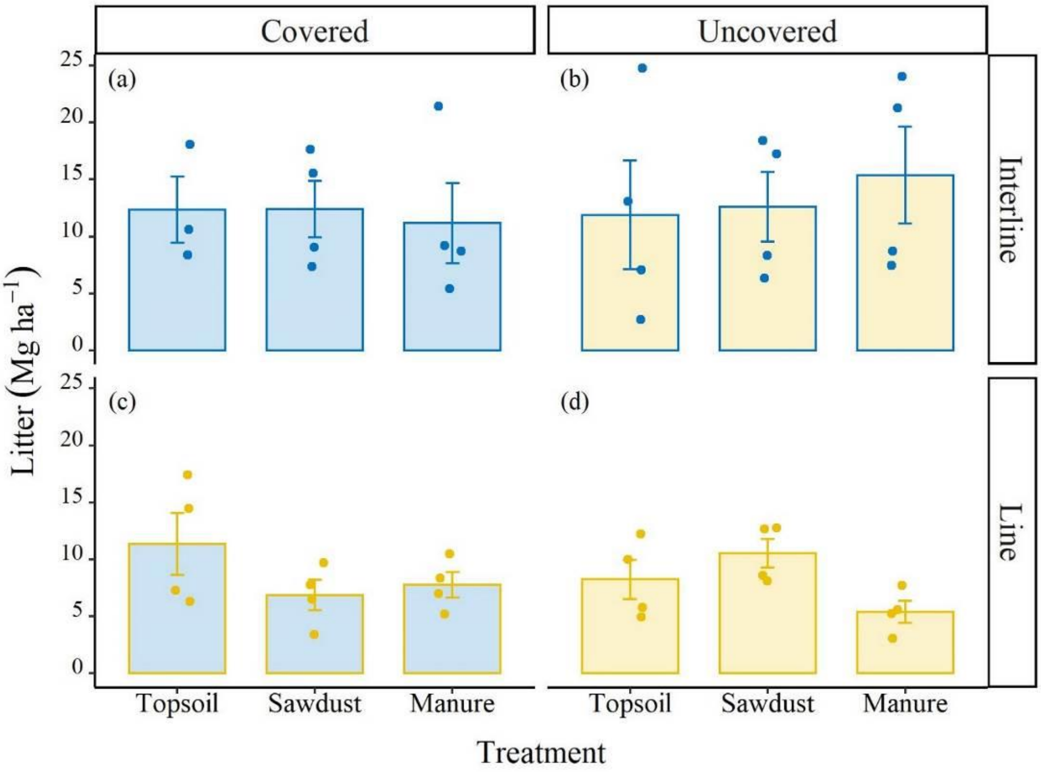


Fig.. 7. Mean (±SE) of the litter stock in the planting rows with (Covered) and without sawdust spreading (Uncovered) under the influence of fertilization treatments in the pits for planting. Each dot represents a sub-sample unit collected from within each plot

3. Discussion

In assessing the effects of organic fertilization on the development of six tree forest species in areas degraded by kaolin mining in the Eastern Amazon, Topsoil showed to be better than Manure. This result was not expected, as it refutes the initial study hypothesis. Manure naturally has a high concentration of nutrients, especially nitrogen. On the other hand, Topsoil was the treatment with the smallest soil cover for non-tree or shrub life forms (27%).

In general, the planted species showed promising results when compared to those in similar studies developed in the Brazilian Amazon (Salomão et al. 2014; Martins et al. 2020a), with a mean increment of more than 1.40 m year-1 and 2.39 cm year-1 for height and diameter at soil height, respectively. This showed that the opening of trenches and the fertilization treatments in the pits benefited plant development. Although the physical variables of the soil were not examined, it is believed that the trenches possibly provided less compacted substrate with the possibility of greater water infiltration, which was directly correlated with plant growth (Orozco-Aceves et al. 2017; Duncan et al 2020). Associated with this, chemical and organic fertilization provide a higher concentration of nutrients to the rhizosphere and, together with the opening of trenches, improve the edaphic conditions and the root development of plants (Longo et al. 2011; Sloan and Jacobs 2013; Yada et al. 2015).

Of the species used in the initial planting, Clitoria fairchildiana, Tachigali vulgaris and Croton matourensis showed the best increment results for both height and diameter (Fig. 3 and 4). These species belong to the ecological group of pioneers and/or initial secondary forest, with rapid growth, and C. matourensis was identified as one of the most representative in the natural regeneration of bauxite mining areas close to this study area (Martins et al. 2020a). The highest mean annual increment in crown area (MAICA) was recorded for C. fairchildiana, which is a favorable characteristic for the restoration of intensely degraded ecosystems, since the soil is quickly covered by the treetops. This reduces the intensity of aggressive grasses and the damage caused by erosion as well as forms a microclimate that is conducive to the development of non-tree or shrub plant life forms and of the edaphic fauna. On the other hand, it was found that there is still a large percentage of uncovered soil, which may be related to the age of planting, as it is considered recent, being only 18 months old. Studies show that, for tropical-forest environments, pioneer species will be gradually replaced by those with a more advanced successional stage in 10 to 20 years of restoration, thereby increasing soil cover, floristic heterogeneity and stratum architecture (Brancalion et al. 2015).

The strong presence of grasses may have influenced plant mortality. As much as the mortality was low and represented only by B. spicata, 50% of it occurred in the Topsoil treatment, justified by the higher frequency of grasses among the treatments. According to Rodrigues et al. (2009), mortality from 0 to 5% is considered acceptable, from 5 to 10% is worrying, and above 10% requires immediate corrective actions. Andrade et al. (2014) recommend that up to 10% of mortality dispersed in the planted area is acceptable. In this study, the mortality rate of 2.4% was quite satisfactory.

In natural regeneration, the low density of tree and shrub species under the sawdust cover may have been influenced by the sawdust decomposition time. The presence of Solanum crinitum, Solanum fulvidum, Cecropia palmata and Vismia guianensis in natural regeneration is a clear indication of the initial succession phase, especially in intensely degraded ecosystems (Eduardo et al. 2012). However, it is expected that these species will be replaced during the succession, thus increasing plant species richness as well as the availability and diversity of resources for the fauna (da Cruz et al. 2020). According to Almeida et al. (2011), the biodiversity of forest fragments, which are also referred to as islands, is related to the size and distance of the forest matrix, that is, larger and less isolated fragments are more favorable for maintaining biodiversity. In addition to these species, Lecythis pisonis and Acacia mangium were found. The former is native to the Amazon, and it is one of the most frequent species in the phytophysiognomy prevailing in the area of the enterprise, thus presenting commercial potential (Siviero et al. 2020), but it has also been indicated for planting in degraded areas of the Brazilian Atlantic Forest (Morais Junior et al. 2019). This species has a long life, and it usually occupies the forest canopy. Its appearance in this experimental area is possibly due to its presence in the forest remnants, where the closest individual is less than 100 m in the southern portion of the planting area (Fig. 1). On the other hand, A. mangium is originally from Oceania, and it is considered an exotic and invasive species that is difficult to control and can cause damage to local biodiversity (Heringer et al. 2019; Koutika and Richardson 2019). This species was planted more than 15 years ago in adjacent areas, in the mining company’s forest restoration programs and, currently, it cannot be controlled.

Litter stock increase means the gradual return of the biogeochemical cycle and nutritional self-sufficiency of vegetation (Londe et al. 2016), as well as greater capacity for water to infiltrate the soil and recover its fertility (Durigan et al. 2016). Although there were no significant differences between the organic fertilization treatments in the pits and in the presence of sawdust, which may be associated with a high data dispersion (Fig. 6), the dry mass values are consistent with those found in other studies conducted in the Amazon (Martins et al. 2018) and other locations worldwide (Zhang et al. 2014).

In a joint analysis of all variables, it was noticed that the trench-opening treatments and fertilization in the pits accelerate the growth of individuals in the initial planting, as it favors greater root development and prevents early tree tipping. In addition, in organic fertilization, no differences were found in filling the pits with topsoil, sawdust or manure. However, it is recommended that monitoring with the inclusion of more indicators for assessing efficiency in the process of restoring degraded ecosystems should be continued (Ribeiro, et al. 2019), as the effects are expected to emerge over the years, mainly with regard to the opening of trenches in order to favor root development.

4. Conclusions

The opening of trenches with the addition of an organic fertilizer plus a chemical fertilizer in the pits was positive in the development of individuals of six species used in the initial planting in an area degraded by kaolin mining in the Eastern Amazon. Of the planted species, *Clitoria fairchildiana, Tachigali vulgaris* and *Croton matourensis* showed the highest mean annual increment in height and diameter, with the latter showing the best result for the crown area increment indicator. The soil has not yet been fully covered with vegetation and litter density and dry mass have not been affected by the presence of sawdust. In addition, it is necessary to perform cost-efficiency analyses in order to demonstrate that the technique can be used in extensive mining areas. However, the results in this study, in the case of heavily degraded areas by kaolin mining, where soils are extremely degraded (physically, chemically and biologically), can be considered promising.

Acknowledgment

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CAPÍTULO IV: SOIL PROPERTIES UNDER DIFFERENT ORGANIC FERTILIZERS IN A RESTORATION SITE AFTER KAOLIN MINING IN THE EASTERN AMAZON.

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Abstract

Mining is one of the economic activities that most degrade ecosystems, and the rehabilitation of such environments in the Brazilian Amazon is still a challenge. The first step is to recover the soil quality for plant reestablishment. In this study was evaluated the effect of different organic fertilizers, supplementary to chemical fertilizers, on the physical and chemical attributes of a minesoil after kaolin mining in the Eastern Amazon, Brazil. Nine trenches measuring 1 m x 40 m and 1 m in depth were opened in a reconstructed area after kaolin mining. They were 6 m apart from each other and filled with topsoil from areas destined for new mine pits. Then 40 cm x 40 cm x 40 cm pits were opened along the trenches. They were 1.5 m apart from each other within each trench, and 400 g pit^{-1} of simple superphosphate, 130 g pit^{-1} of urea and 130 g pit^{-1} of potassium chloride were applied in five treatments: three treatments along the trenches, in the planting rows with; *i)* addition of topsoil; *ii)* sawdust; *iii)* cattle manure, and two treatments between the planting rows; *iv)* sawdust; and *v)* without sawdust. Two hundred and fifty seedlings of six heliophilous tree species were planted, being randomly distributed. One hundred and forty-four disturbed (original structure altered) and 144 undisturbed (structure equal to the original soil) samples were collected for evaluation of the physical and chemical attributes of minesoil. Besides soil, other variables were assessed: plants abundance, height, diameter at breast height as well as litter stock. The treatments did not differ significantly in relation to the effects on abundance, height, diameter and litter stock, either in the planting rows or between them. The organic matter was higher in the Manure treatment at depths of 0.0-0.1 and 0.2-0.4 m. The sawdust coverage between trenches increased Ca and base saturation, but decreased N due to the high Carbon/Nitrogen ratio. Planting using trenches, topsoil, chemical and organic fertilization and sawdust coverage resulted in good physical and chemical properties of the soil and enabled greater efficiency in restoring the area mined for kaolin in the Amazon.

Keywords: Forest restoration; mining, minesoil, trench, topsoil.

1. Introduction

Kaolin is a widely exploited mineral in the Brazilian Amazon. It has non-metallic characteristics and is very useful, mainly in pulp bleaching. The state of *Pará*, Brazil, is the world's largest kaolin exporter. In 2018, the state exported 1.5 million tons of kaolin, with a return of US$ 168 million (Imerys Caulim, 2020; SINMINERAL, 2019). Despite the economic importance of mining, its negative environmental impacts are inevitable, and recovering extensive landscapes, with ecosystem structure and function restoration, is a difficult and challenging task (Dudley et al., 2018).

Soil rebuilding after a degradation process is an essential factor for a successful restoration trajectory. There is a close relationship between the different techniques and methods for revegetation and restoration of environmental integrity (Zhou et al., 2017). Restored soils are essential for nutrient and organic-matter cycling in the pedosphere, and for generating nutritional sources and water balance that guarantees plant productivity and sustains biodiversity (Dominati et al., 2010).

The soils removed prior to the mining process are unstructured, as there is a mixture between surface and subsurface horizons, which causes physical, chemical and microbiological changes (Feng et al., 2019). After the topographic reconstruction of the relief the new soil, from fragmented rocks and sterile and organic material, is referred to as minesoil or technosols (Ahirwal et al., 2017).

Despite all guidelines for topographic reconstruction of the relief, in the Amazon, the newly mined areas have physical limitations, mainly due to soil compaction (Brasil Neto, 2017; Souza, 2018). Minesoils generally originate from the relief reconstruction process in the deposition stages of sterile post-mining material and topsoil during the pit closure after the ore mining. This process results in decreased total porosity of the soil and increased mechanical resistance, thus impairing root growth (Cambi et al., 2015; Feng et al., 2019; Twum and Nii-Annang, 2015). In addition, compaction hinders root penetration and water infiltration, making minesoil more prone to erosion and fertility depletion (Cambi et al., 2015; Guebert and Gardner, 2001).

The evaluation of a minesoil must occur in an integrated manner, with analyses of its physical, chemical and microbiological properties before and after mineral extraction, including its Cation Exchange Capacity (CEC) and nutrient availability (Pant et al., 2017). Litter decomposition is also important in restoration, as soil microflora and fauna are fundamental in the formation of biogenic structures and aggregates that influence organic matter distribution (Frouz et al., 2013).

At the beginning of the restoration process after mining, fertilization is important to provide its initial establishment and plant growth. In the Amazon, such procedure is even more relevant, as the soils have low natural fertility and high acidity levels. Chemical fertilization is most often used to correct acidity problems and deficiencies in soil fertility (Grant et al., 2007). Its efficiency occurs mainly in the surface layer of the soil (0-15 cm), acting in improving mineralization in the organic layer and in ecosystem functioning (Court et al., 2018; Grant et al., 2007). On the other hand, organic fertilization benefits moisture retention, nutrient provision, microbiota increase and soil structure (Simões et al., 2015).

Organic fertilization and lime application in minesoils, followed by planting species with high biomass production, increases soil carbon sequestration capacity (Feng et al., 2019; Shrestha and Lal, 2011). In this context, it is necessary to make efficient options in order to have effective ecological restoration, applying operational methods and procedures in accordance with the local reality. In this way, our work tackles the following questions: a) Does the application of sawdust and bovine manure improve physical and chemical soil attributes? b) Do these supplementary organic fertilizers speed up growth of planted species and the litter stock? Thus, our study aimed to evaluate the effect of different organic fertilizers, supplementary to chemical fertilizers, on the physical and chemical attributes of the soil, plant growth and litter stock in an experimental area after kaolin mining in the Eastern Amazon.

2. Material and Methods

2.1 Study area

The study was conducted in the area known as *Cota 85*, which was mined for kaolin extraction in 2013. The area belongs to *Pará Pigmentos S.A. (PPSA)*, which is part of the French mining company *Imerys*, located in the municipality of *Ipixuna do Pará*, state of *Pará*, Brazil. Land reconstruction took place between the end of 2015 and beginning of 2016, and the choice for the area was due to its characteristics, which are similar to most of the environments found after kaolin mining in the Amazon, with unstructured soil horizons and high soil compaction (Fig. 1).

According to Koppen’s classification, the region’s climate is the *Am* type, wet equatorial, with a moderate dry season from June to November (Alvares et al., 2013), mean annual rainfall of 1,750 - 2,500 mm (Andrade et al., 2017) and average temperature of 26.7 °C. The predominant vegetation is the lowland dense ombrophilous forest (IBGE, 2012). The soils are well drained, thick and leached, with low natural fertility with predominance of yellow dystrophic latosols (João et al., 2013).

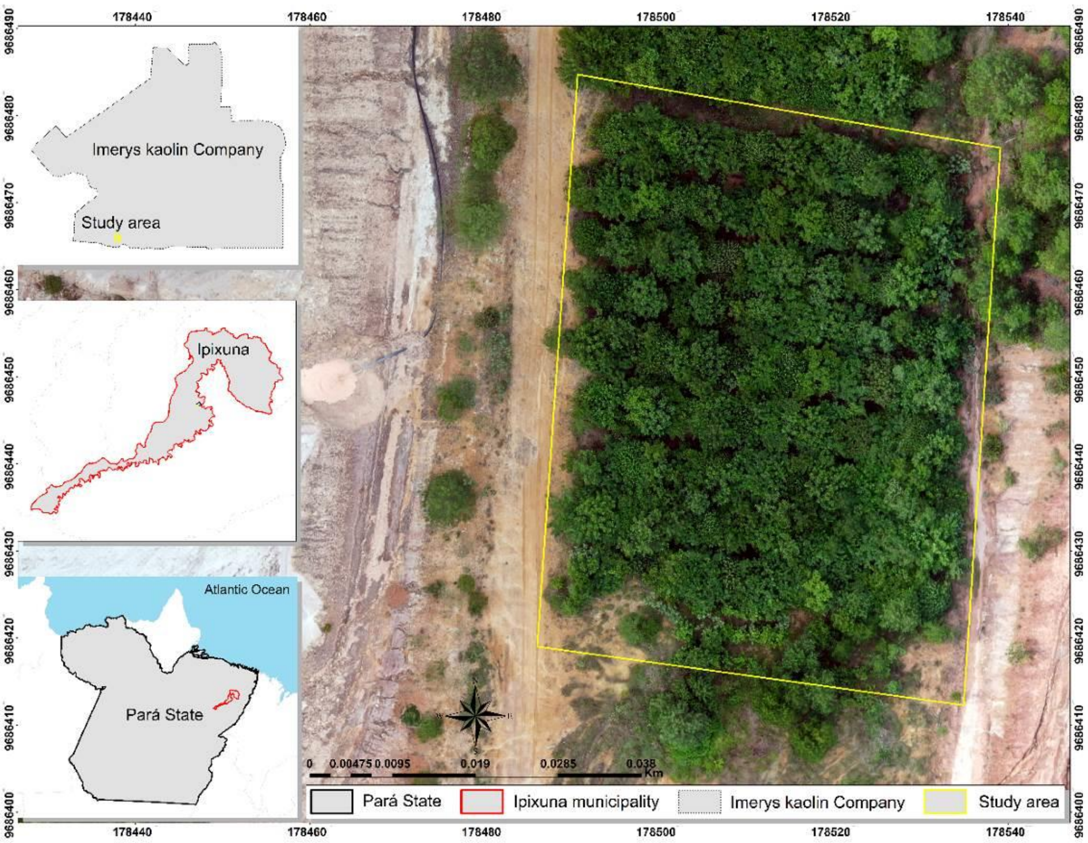

Figure. 1. Study area (PPSA mine) located in the municipality of Ipixuna do Pará, Pará state/Brazil, under restoration after kaolin mining.

2.2. Experimental design

The area was prepared for the experiment at the end of the dry season, in November 2017, on 0.35 hectares of minesoil, with the initial planting of tree species seedlings occurring at the beginning of the rainy season, in January 2018. In this area, nine trenches measuring 1 m x 40 m and 1 m in depth were opened. They were separated from each other by a distance of 6 m between the rows. The trenches were filled with topsoil extracted at a depth of 1 m from adjacent areas to be mined.

After filling the trenches with topsoil, 40 cm x 40 cm x 40 cm pits were opened along the length of each trench, at a distance of 1.5 m apart from each other. Then 400 g pit^{-1} of simple superphosphate, 130 g pit^{-1} of urea and 130 g pit^{-1} of potassium chloride (KCl) were applied, divided into two applications with a 60-day interval. The inorganic fertilization was previously set by the mining company to speed up the initial growth of planted tree species. Finally, the supplementary organic compound was added in three different treatments: a) topsoil, b) sawdust and c) bovine manure, each comprising the pits in three trenches (Table 1). The topsoil treatment served as a control, that is, without the addition of new inputs, but only the topsoil that filled the trench. The spaces between rows, or the 6-m space between the nine trenches, were divided into two conditions: (a) with the addition of a 10-cm covering of sawdust over the soil; and (b) without sawdust addition. Each of these treatments occupied 50% of the total 0.35-ha area of the experiment (Fig. 2). The disposed sawdust consisted of residues from nearby sawmills, in the municipality of *Ipixuna do Pará* (Fig. 2).

Figure. 2. Simulation of the experimental area 18 months after its establishment with the distribution of the three treatments of organic fertilization (topsoil, sawdust and manure) and the 50% of the area covered by a 10-cm sawdust layer in experimental restoration area after mining, PPSA mine, Eastern Amazon, Brazil.

Table 1. Treatments of organic matter and sawdust cover in the soil preparation for the initial seedling planting for restoration of a degraded area by kaolin mining, PPSA mine, Eastern Amazon, Brazil

Treatments	Description	Place/Site	Trench preparation
Topol.	Topsoil (Control)	Planting Line	-
Sados	Topsoil + Sawdust	Planting Line	40 liters of wood sawdust and topsoil.
Manure	Topsoil + Manure bovine	Planting Line	40 liters of bovine manure and topsoil.
Covered	Sawdust	Interlining	-
Uncovered	Without Sawdust	Interlining	-

Recommendations on soil fertilization for the initial planting of tree species were carried out through a chemical and grain size characterization of the soil built in the depths 0-0.1 m, 0.1-0.2 m and 0.2-0.4 m after filling the nine trenches with topsoil (Tables 2 and 3).

Table 2. Initial chemical characterization of the most superficial soil layers under recovery after kaolin mining at PPSA mine, Eastern Amazon, Brazil.

Treatment	MO	C	N	C/N	P	Al	Ca	Mg	K	CEC Total	CEC Effective	V%	m%	pH
	-------- g kg^{-1} ------ -				mg dm^{-}	----------------- cmol$_c$ dm^{-3} ------------- -						----- % --- -		H_2O
	---------- 0.0-0.1 m ----------													
Topsoil	6.9	4.0	6.8	0.59	0.6	0.9	0.05	1.2	0.02	4.3	2.1	29.9	40.8	5.0
Sawdust	6.2	3.6	5.5	0.65	0.3	0.8	0.09	1.2	0.02	4.2	2.2	32.0	38.6	4.7
Manure	4.7	2.7	6.8	0.40	0.3	0.9	0.07	1.2	0.02	4.1	2.2	31.9	40.3	4.8
	---------- 0.1-0.2 m ----------													
Topsoil	7.1	4.1	8.2	0.50	0.3	1.0	0.14	0.2	0.01	3.2	1.3	10.8	73.9	5.0
Sawdust	5.3	3.1	6.8	0.46	0.4	0.9	0.17	1.2	0.02	4.1	2.3	33.8	39.2	4.7
Manure	4.7	2.7	6.8	0.40	0.5	0.9	0.09	1.2	0.01	4.3	2.3	32.0	40.1	4.7
	---------- 0.2-0.4 m ----------													
Topsoil	8.0	4.6	6.8	0.68	0.3	0.9	0.13	1.1	0.01	3.8	2.2	34.0	41.0	4.9
Sawdust	4.6	2.7	6.8	0.40	0.4	1.0	0.11	1.1	0.01	4.3	2.2	29.7	43.4	5.0
Manure	4.8	2.8	6.8	0.41	0.9	1.0	0.13	0.3	0.01	3.2	1.5	12.0	66.8	4.9

Legend: MO (Organic Matter, C (Carbon), C/N (Carbon/Nitrogen ratio), P (Phosphorus), Al (Aluminum), Ca (Calcium), Mg (Magnesium), K (Potassium), CEC (Cation Exchange Capacity), V% (Base Saturation), m% (Aluminum Saturation) and pH in H_2O.

Table 3. Initial physical characterization of the most superficial soil layers under recovery after kaolin mining at PPSA mine, Eastern Amazon, Brazil.

Treatment	Depth (m)	Sand	Silt	Clay	Texture class*
			$g\ kg^{-1}$		
Topsoil	0.0-0.1	578	92	330	sandy clay loam
Sawdust		551	72	377	sandy clay
Manure		594	83	323	sandy clay loam
Topsoil	0.1-0.2	556	79	365	sandy clay
Sawdust		506	97	397	sandy clay
Manure		583	105	312	sandy clay loam
Topsoil	0.2-0.4	554	76	370	sandy clay
Sawdust		528	80	393	sandy clay
Manure		554	103	343	sandy clay loam

The texture class was determined according to the United States Department of Agriculture (USDA, 2014). Where: Topsoil = only topsoil; Manure = topsoil + bovine manure; Sawdust = topsoil + sawdust.

From the establishment of the experimental treatments using topsoil, sawdust and manure, 250 seedlings of six heliophilous tree species were planted with average height of 27.56 ± 8.87 cm, distributed in the three treatments (Table 4). The planting order of the species in the trenches (planting rows) was made random, thus allowing, at most, the repetition of two individuals of the same species consecutively (Appendix 1). The choice of six heliophilous tree species was made according to: *i*) ecological group; *ii*) rapid growth; *iii*) high survival; *iv*) N fixation in the soil; and *v*) high litter production. The seedlings were produced in the company's own nursery for a period of six months before planting. The seeds for seedling production were collected from mother trees in the urban area of the PPSA mine and from native forests in the mine vicinity.

Table 4. List of species and number of individuals planted for the restoration of a degraded area after kaolin mining, PPSA mine, Eastern Amazon, Brazil.

Species	Topsoil	Manure	Sawdust	Total
Byrsonima spicata (Cav.) DC.	14	14	14	42
Clitoria fairchildiana R.A. Howard	13	13	15	41
Croton matourensis Aubl.	14	14	14	42
Inga edulis Mart.	14	14	14	42
Syzygium cumini (L.) Skeels	14	15	13	42
Tachigali vulgaris L.F. Gomes da Silva & H.C. Lima	14	13	14	41
Total	83	83	84	250

Where: Topsoil: only topsoil; Manure: topsoil + bovine manure; Sawdust: topsoil + sawdust.

Eighteen months after planting, plots measuring 2 m x 2 m (4 m^2) were distributed entirely randomly over the trench areas and between the rows. Evaluation was conducted separately in: (a) planted trees, sampled in 48 plots and (b) trees of natural regeneration quantified between the rows, totaling 24 plots. In addition to the tree vegetation, soil samples with disturbed and undisturbed structure and the quantification of litter stock were collected.

2.3. Analyzed variables

2.3.1. Minesoil

In order to evaluate the physical and chemical attributes of minesoil, 144 disturbed samples and 144 undisturbed soil samples were collected. The disturbed samples were randomly collected at three points of each plot and, after homogenization, the composite samples originated at depths 0.0-0.1 m; 0.1-0.2 m and 0.2-0.4 m. Undisturbed samples were collected in the center of the plots by means of 100-cm^3 volumetric rings at the same depths as those of the disturbed samples.

With disturbed samples, the pH in H_2O was measured as well as the amounts of potassium chloride (KCl), calcium (Ca), magnesium (Mg), aluminum (Al), potassium (K), phosphorus (P), potential acidity (H+Al), organic matter (OM). With undisturbed samples, soil bulk density (Sbd) was determined by using the volumetric-ring method (Eq.1), total soil porosity (Tp), considering particle density (Pd) 2.65 kg dm^{-3}, average of mineral soils (Eq.2), macro and micro porosity, soil water retention (θ), pore diameter and available water content. Laboratory analyses of the physical and chemical attributes followed the determination methods described by IUSS Working Group WRB (2015). They were conducted at the Soil Laboratory of the Brazilian Agricultural Research Corporation (EMBRAPA - Eastern Amazon) in *Belém-PA*.

$$Sbd\ (kg\ dm^{-3}) = \frac{Dry\ sample\ weight\ (g)\ at\ 105\ °C}{100} \qquad \text{Eq.1}$$

$$Tp(m^3m^{-3}) = \left(1 - \frac{Sbd}{Pd}\right)100 \qquad \text{Eq.2}$$

Microporosity was obtained from the soil water retention curve, at a tension equivalent to 6 kPa. Macroporosity resulted from the difference between total porosity and microporosity. Soil water retention was obtained at tensions of 6, 10, 30, 100 and 1,500 kPa, with disturbed samples previously saturated with water, on a porous ceramic plate, by applying the abovementioned tensions and using the equipment referred to as pressure membrane apparatus. Once these points (θ, θ m) had been determined, the water retention curves were adjusted, according to the model proposed by Van Genuchten (1980).

$$\theta = \theta r + \frac{\theta s - \theta r}{[1 + (a|\Psi mat|)^n]^m} \qquad \text{Eq.3}$$

Where: = soil moisture (cm3 cm-3);   = residual volumetric moisture (cm3 cm-3); = saturated volumetric moisture (cm3 cm-3); mat = matrix potential (kPa); , n and m = empirical parameters of the equation. Such adjustment was performed by the method that considers: = max, with m = 0 and, = min, with m = -1,500 kPa, according to Carvalho (1999).

2.3.2. Vegetation

The variables measured in tree and shrub species were: total height (H_t), diameter at soil height (DSH) for regenerating individuals and diameter at breast height (DBH). H_t was measured with a 2 m long graduated rod, where individuals higher than 2 m had H_t estimated.

2.3.3. Litter stock

The litter stock was sampled in February 2019, through a template measuring 0.25 m x 0.25 m and 0.10 m in height. Samples were collected at the center of all plots. After collection, the samples were sent to the Soil Laboratory of the Federal Rural University of Amazonia, where they were dried at 60 °C until reaching constant mass, which was then weighed on an analytical balance of 0.01 g precision.

2.4. Statistical analysis

For statistical analysis, the data were submitted to normality analysis by the Shapiro-Wilk test (Shapiro and Wilk, 1965), Levene's homoscedasticity test (Levene, 1960) and, subsequently, to the analysis of variance (ANOVA). The means of variables for the pit fertilization treatments in the trenches were submitted to Tukey's test ($p<0.05$) (Tukey, 1953), while the variables for between the rows were submitted to Student's t test ($p<0.05$) (Student, 1908). For all statistical analyses, the R software program, version 4.0.1 (R Core Team, 2020) was used.

3. Results and Discussion

3.1. Attributes of vegetation and litter

The topsoil, sawdust and manure treatments did not differ significantly in terms of the effects on woody plant abundance, height, diameter and litter stock (Table 5). The abundance of planted individuals was due to high survival (99%) in all treatments. The results obtained showed that the planting of seedlings in the trenches with topsoil was efficient in the initial establishment of the species, promoting the rapid initial covering of the reconstructed soil. Regarding the evaluated treatments, the non-difference indicates that the initial chemical fertilization mixed with topsoil was sufficient to promote tree growth.

Table 5. Mean ± standard deviation of the absolute abundance of planted individuals, total height (H_t), diameter at breast height (DBH) and litter stock, 18 months after the experiment starting in a recovering area after kaolin mining, PPSA mine, Eastern Amazon, Brazil.

Treatment	Abundance (Ind. ha^{-1})	Total height (H_t) (m)	DBH (cm)	Litter stock (Mg ha^{-1})
Topsoil	6,917 ± 145	3.43 ± 1.13	4.0 ± 2.1	9.79 ± 4.53
Manure	6,917 ± 145	3.18 ± 1.00	3.9 ± 2.1	6.61 ± 2.29
Sawdust	7,000 ± 0	3.31 ± 0.86	4.1 ± 1.9	8.69 ± 3.10

There was no statistical difference among variables (ANOVA; $p > 0.05$). Where: Topsoil: only topsoil; Manure: topsoil + bovine manure; Sawdust: topsoil + sawdust.

The treatments involving litter between the rows did not differ significantly in abundance, height, diameter at breast height (DBH) and litter stock (Table 6). At 18 months, abundant regenerating vegetation was found in the forest succession process. The recovery of degraded areas close to forest fragments is benefited by the potential establishment of vegetative propagules (Almeida, 2016). During natural regeneration, the species present in the soil seed bank are referred to as “ecological memory” (Reid, 2015; Sun et al., 2013). Such germinative potential is extremely important for the vegetation succession process.

The litter stock was 9.79, 8.69 and 6.61 Mg ha^{-1} for topsoil, sawdust and manure, respectively, which did not differ statistically among treatments (Table 5). This can be explained by the presence of pioneer species in all treatments, which have rapid growth and are more adapted to the strong light incidence and climate conditions of the region (Martins et al. 2018).

Table 6. Mean ± standard deviation of the absolute abundance of individuals from natural regeneration, Height, Diameter at breast height (DBH) and litter stock in covered area (Covered) and not covered (Uncovered) by sawdust, 18 months after the experiment starting in a recovering area after kaolin mining, PPSA mine, Eastern Amazon, Brazil.

Treatment	Abundance (Ind. ha^{-1})	Total height (H_t) (m)	DBH (cm)	Litter stock (Mg ha^{-1})
Covered	1,875 ± 2,175	0.95 ± 1.31	2.78 ± 4.32	11.94 ± 5.26
Uncovered	3,750 ± 3,925	1.26 ± 1.35	3.46 ± 4.29	13.28 ± 7.57

There was no statistical difference between variables (Student's t test; $p > 0.05$). Where: Covered and Uncovered with sawdust between the planting lines.

1.1.2 Soil organic matter

In the trenches, the organic matter (OM) content in the soil was significantly higher in the manure treatment as compared to that with sawdust addition (Fig. 3). The higher OM content in the manure treatment was mainly due to the fact that manure decomposition and OM incorporation into the soil is faster when compared to those of sawdust. Sawdust has higher lignin content in its anatomical structure, making it difficult for rapid decomposition by soil micro and macrofauna (Nguyen and Marschner, 2017). In addition, it is essential to emphasize the positive effects of the tree species planted, which normally contribute to the coverage and OM incorporation into the soil through the litter (Rocha et al., 2016; Brasil Neto et al., 2021). They could have influenced the amount of OM, since there was no difference between the topsoil and manure treatments as regards OM content.

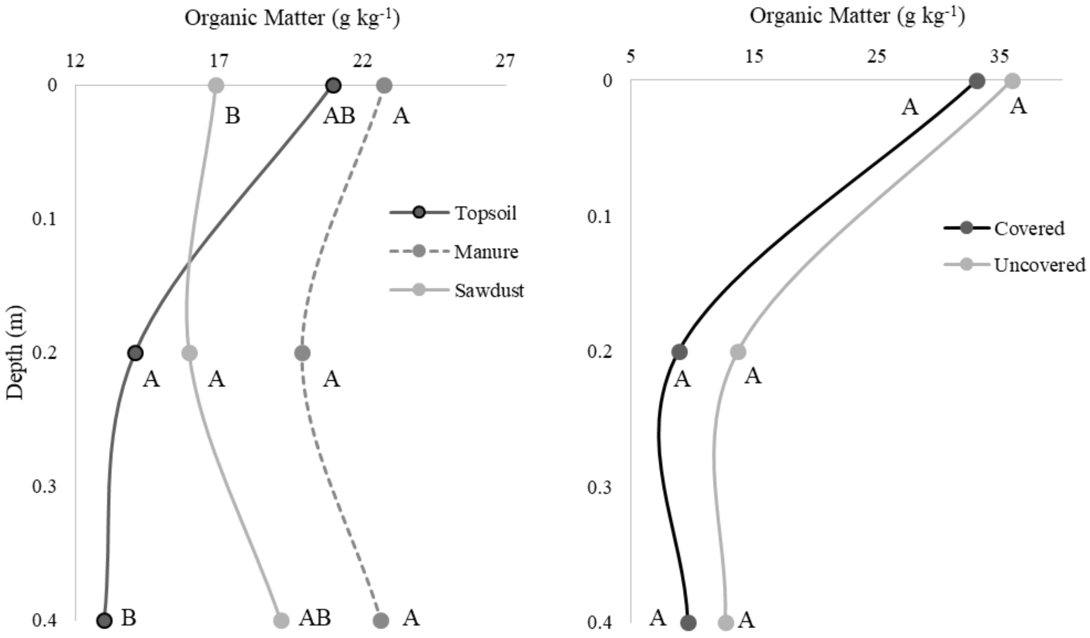

Figure. 3. Organic matter of the substrate in treatments consisting of Topsoil, Sawdust and Manure, in addition to covered and uncovered soil by sawdust evaluated in restoring area after kaolin mining, PPSA mine, Eastern Amazon, Brazil. Where: Topsoil = only topsoil; Manure = topsoil + bovine manure; Sawdust = topsoil + sawdust and; Covered and Uncovered soil in between planting lines with sawdust. Letters indicate statistical differences by the Tukey test (5% significance).

As for the organic matter content resulting from the treatments with sawdust addition to the soil surface (covered) and sawdust non-addition (uncovered), there were no significant differences after 18 months of restoration. This may also be associated with slower decomposition, which is characteristic to sawdust (Bollen and Lu, 1957). However, in depth 0.0-0.1 m, the mean values were higher than 33.0 g kg^{-1}, which are classified as high (Sobral et al., 2015). These results were mainly due to the litter effect from the regenerating tree species on the site.

It is common to find decreased organic matter content in soils that have been recently rebuilt after mining as a result of soil removal and storage (Anderson et al., 2008; Angst et al., 2018), as well as a mixture of substrate from different depths in the reconstruction process (Feng et al., 2019). Increase in organic matter content is fundamental for the ecosystem restoration process, considering that such process contributes to soil structuring and nutrient cycling and retention, in addition to biological activity (Gmach et al., 2020).

Regarding soil bulk density in the three studied depths, there was no significant difference between the treatments in the trenches and those between the rows. These results are attributed to the short time since the experiment's start (18 months), considering that the vegetation was still in its initial succession phase, with the natural substrate structuring processes still incipient (Tables S1 and S2; supplementary material). Soil bulk density was higher in the planting rows as compared to that between the rows under natural regeneration (Tables 7 and 8), due to the exposure of the highly porous and unstructured substrate and the covering of the soil by the planted and regenerating vegetation. Some studies have identified significant differences in soil bulk density in the initial layers, especially in the first 0.1 m (Rossetti and Centurion, 2015; Silva et al., 2016).

Soil bulk density varied from 1.19 to 1.27 kg dm^{-3} in the planting row (over the topsoil-covered trench) and from 1.22 to 1.39 kg dm^{-3} between the rows. These figures were below the critical limit of 1.55 kg dm^{-3} for plant growth in agricultural and forest environments (Reichert et al., 2003) for soils with clay content between 200 and 500 g kg^{-1}. It was not possible to detect significant differences between treatments for soil bulk density, total porosity, macroporosity or microporosity between the topsoil, sawdust, and manure treatments or in the treatments between covered and uncovered trenches (Tables 7 and 8).

The available water content was higher in the covered trenches as compared to the uncovered ones at a depth of 0.0-0.1 m. These results can be attributed to the micropores present in the covered treatment (Table 7). Different soil management techniques can result in changes in water movement and consequently in infiltration problems (Aquino et al., 2014; Soares et al., 2016). Compaction is one of the biggest issues in restoration after mining, and it occurs due to soil disruption in the ore mining process and the constant traffic of machinery during relief reconstruction (Twum and Nii-Annang, 2015).

Results suggest that the use of topsoil in trenches caused a movement of particles due to substructure disruption, possibly leading to densification resulting from pore obstruction by leached solid particles. This generally causes the sealing of substrate layers with pore clogging and consequent soil macroporosity reduction and microporosity increase, resulting in higher soil bulk density. In addition, rainfall, depending on its intensity, may be one of the main factors responsible for such process, as the detachment and transportation of sediments, for example, promotes soil loss due to flooding (Bertol et al., 2007; Bertoni and Lombardi Neto, 2017; Panini et al., 1997).

With regard to water retention in the soil, the Van Genuchten (1980) model was efficient in adjusting the retention curves, with high determination coefficients to adjust the data ($R^2 > 0.995$) (Table 7 and Fig. 4). Under the conditions studied, water loss from saturation to field capacity was high, which is due to the macropores of the mineral soil. These macropores were formed mainly by the effect of the initial planting established in the trenches and also by the amount of sand fraction (> 500 g kg^{-1}). The chemical attributes of the soil had few significant effects, considering that the pores are responsible for water retention and storage, results also found in other studies (Carmo et al., 2018; Furquim et al., 2018).

Table 7. Water retention results by the Van Genuchten equation (1980), applied to soil samples under experimental conditions in different treatments and depths of a restoring area after kaolin mining, PPSA mine, Eastern Amazon, Brazil.

Treatment	Depths (m)	Variables					
		a	m	N	Θr	Θs	R^2
		($1cm^{-1}$)	------------($m^3\ m^{-3}$)--------------				
Topsoil	0-0.1	3.967	0.076	2.574	0.072	0.446	0.999
Manure		0.003	1.436	0.185	0.001	0.459	0.998
Sawdust		23.140	0.234	0.392	0.001	0.479	0.995
Covered		6.881	0.050	2.334	0.001	0.494	0.998
Uncovered		15.637	0.071	2.078	0.100	0.499	0.997
Topsoil	0.1-0.2	1.716	0.078	3.301	0.084	0.427	0.999
Manure		0.003	1.453	0.178	0.001	0.441	0.999
Sawdust		0.002	1.516	0.169	0.001	0.463	0.997
Covered		2.892	0.065	2.757	0.072	0.451	0.996
Uncovered		2.967	0.095	2.729	0.152	0.492	0.998
Topsoil	0.2-0.4	1.045	0.089	4.083	0.125	0.445	0.999
Manure		0.002	1.692	0.173	0.001	0.464	0.998
Sawdust		0.005	1.369	0.179	0.001	0.454	0.998
Covered		2.905	0.045	2.717	0.006	0.418	0.996
Uncovered		4.328	0.059	0.564	0.086	0.442	0.999

Legend: θr = residual volumetric moisture ($cm^3\ cm^{-3}$); θs = saturated volumetric moisture ($cm^3\ cm^{-3}$); a, n and m = empirical parameters of the equation; R^2 = determination coefficient, of the following treatments: Where: Topsoil = only topsoil; Manure = topsoil + bovine manure; Sawdust = topsoil + sawdust and; Covered and Uncovered soil in between planting lines with sawdust.

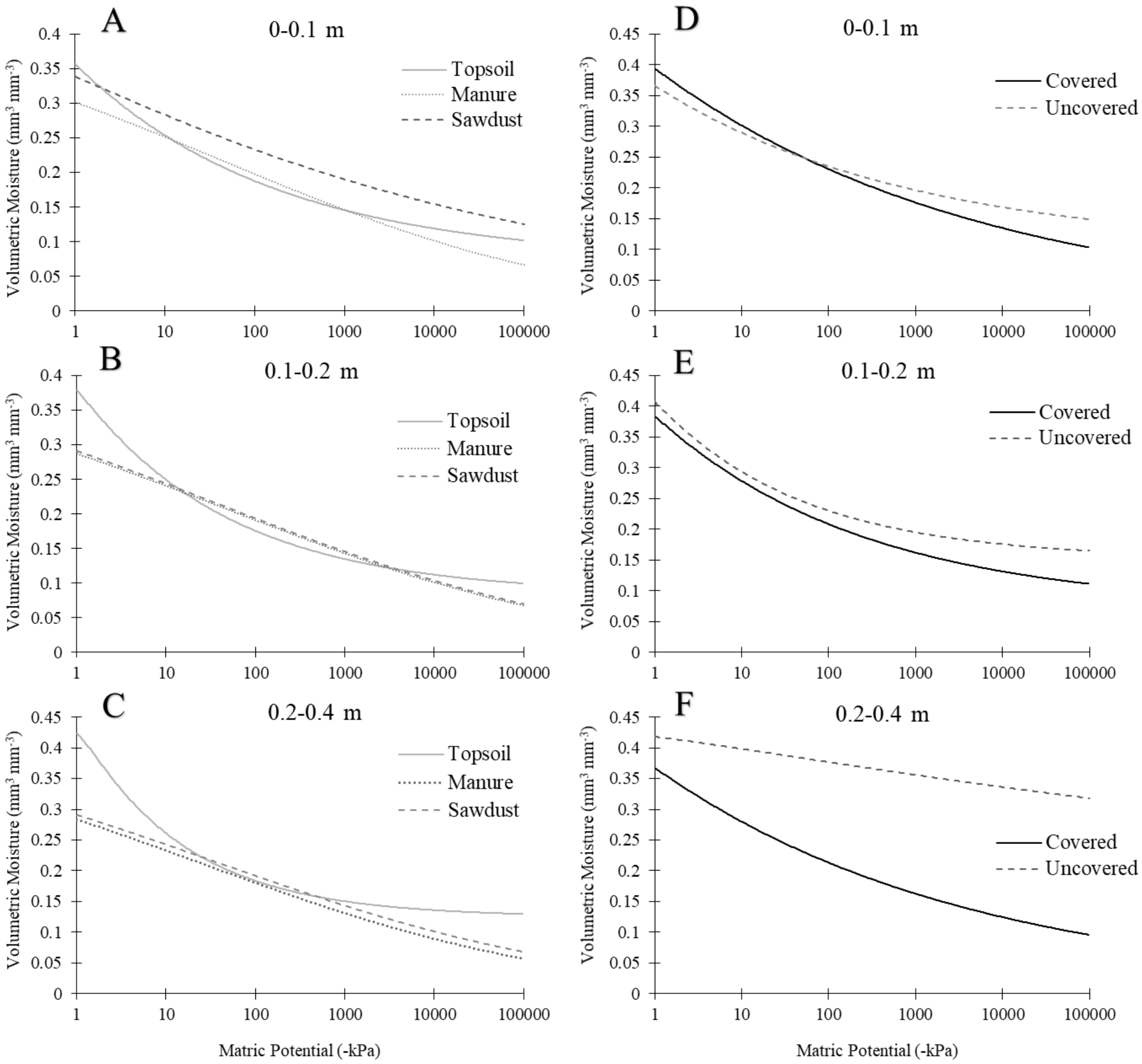

Figure. 4. Soil water retention curve estimated by Van Genuchten equation, under experimental conditions Topsoil, Manure and Sawdust (A, B e C), Covered and Uncovered by sawdust (D, E e F) in the depths 0-0.1, 0.1-0.2 and 0.2-0.4 m, after kaolin mining, PPSA mine, Eastern Amazon, Brazil. Where: Topsoil = only topsoil; Manure = topsoil + bovine manure; Sawdust = topsoil + sawdust and; Covered and Uncovered soil in between planting lines with sawdust.

In the 10 to 1,500 kPa range, water retention was greater in natural regeneration areas (between the rows) at all depths evaluated, in which there was no topsoil transposition. These results are associated with organic matter and also with the larger number of micropores found in these systems, reducing the retention curve slope. Higher proportion of micropores reduces drainage and increases soil water storage through the matrix force, also increasing the soil water retention curve (Dexter, 2004; Torres et al., 2014). The results indicate that the opening of trenches favored soil covering and species development, which normally improves water infiltration and soil quality (Duncan et al., 2020; Orozco-Aceves et al., 2017).

Regarding chemical attributes, most parameters evaluated in the soil, in different treatments, were in proportions considered medium and low for good plant development (Sobral et al., 2015; Table 8). This was probably due to the fact that fertilization was carried out only on the planting row and the soil or substrate was originally of low fertility, in addition to the degradation promoted by mining activity. As observed for the physical attributes of the soil, no significant effects of different treatments on the evaluated chemical attributes were detected, considering that fertilization, whether chemical or organic with sawdust or manure, had been applied only in the pit where seedlings were planted. Although with no significant effects of treatments on chemical attributes during the initial phase of the ecological restoration process, the procedures adopted in all treatments in the planting rows showed positive results.

Table 8. Chemical attributes of the soil by each treatment (Topsoil = only topsoil; Manure = topsoil + bovine manure; Sawdust = topsoil + sawdust), Topsoil + sawdust (Sawdust) and Topsoil + bovine manure (Manure) applied in trenches in a restoring area after kaolin mining, PPSA mine, Eastern Amazon, Brazil.

Treatment	C	N	C/N	P	Al	Ca	Mg	K	CEC Total	CEC Effective	V%	m%	pH
	-----g kg^{-1}----			mg dm^{-3}	-------------------$cmol_c$ dm^{-3}-----------------						%	%	H_2O
	------------0-0.1 m------------												
Topsoil	12.2^{ab}	0.83^{a}	14.4^{b}	5.0^{a}	0.46^{a}	2.4^{a}	0.40^{c}	0.09^{a}	7.2^{a}	3.1^{a}	32.4^{a}	22.9^{a}	4.7^{a}
Sawdust	9.8^{b}	0.62^{b}	17.3^{ab}	6.6^{a}	0.48^{a}	1.3^{b}	0.28^{b}	0.07^{b}	5.8^{b}	2.2^{b}	28.1^{b}	25.9^{a}	4.8^{a}
Manure	13.2^{a}	0.76^{a}	19.9^{a}	3.0^{b}	0.35^{a}	1.7^{ab}	0.53^{a}	0.09^{a}	6.7^{ab}	2.7^{ab}	35.9^{a}	13.2^{b}	4.6^{a}
	------------0.1-0.2 m------------												
Topsoil	8.6^{b}	0.57^{b}	14.0^{b}	2.0^{b}	0.70^{a}	0.9^{b}	0.20^{b}	0.04^{b}	5.0^{b}	1.8^{b}	21.6^{b}	42.2^{a}	4.5^{a}
Sawdust	9.3^{b}	0.57^{b}	15.4^{b}	2.9^{a}	0.78^{a}	0.8^{b}	0.22^{b}	0.07^{a}	5.1^{b}	1.9^{b}	20.1^{b}	46.3^{a}	4.6^{a}
Manure	22.3^{a}	0.76^{a}	48.6^{a}	1.9^{b}	0.47^{b}	2.1^{a}	0.45^{a}	0.07^{a}	7.1^{a}	3.1^{a}	32.6^{a}	20.8^{b}	4.7^{a}
	------------0.2-0.4 m------------												
Topsoil	24.2^{a}	0.58^{b}	46.8^{a}	1.7^{a}	0.68^{ab}	0.9^{b}	0.23^{b}	0.04^{a}	4.8^{b}	1.9^{b}	22.7^{b}	41.5^{a}	4.3^{b}
Sawdust	11.1^{b}	0.60^{b}	17.8^{b}	1.3^{b}	0.81^{a}	0.9^{b}	0.27^{b}	0.03^{a}	5.8^{ab}	2.1^{b}	19.7^{b}	44.9^{a}	4.6^{ab}
Manure	13.1^{b}	0.88^{a}	16.5^{b}	1.6^{a}	0.51^{b}	1.9^{a}	0.43^{a}	0.04^{a}	6.6^{a}	2.9^{a}	31.3^{a}	27.2^{b}	4.8^{a}

Legend: C - Carbon; N - Nitrogen; C/N – Carbon/Nitrogen ratio; P - Phosphorus; Al - Aluminum; Ca - Calcium; Mg - Magnesium; K - Potassium; SB - Sum of bases; CEC - Cation exchange Capacity. V% - Base saturation and m% - Aluminum saturation. * Letters indicate statistical differences (Tukey's t test; $p > 0.05$).

In the analysis among planting rows, it was found that the use of sawdust (covered) increased the Ca content and effective CEC as well as reduced soil acidity at a depth of 0-0.1 m as compared to those in the uncovered trench (Table 9). These results are probably associated with the effect of sawdust on the surface, on which organic material provides essential nutrients to reduce the effect of soil acidity and increase cation exchange capacity, promoting several benefits for soil fertility.

In addition, there was a significant difference in N content and in the C/N ratio between the covered and uncovered treatments, with the highest C/N ratio observed in the sawdust treatment (Table 9). These results can be attributed to the greater amount of carbon in sawdust, causing microorganisms to require N contained in the soil to perform decomposition, thus decreasing the availability of such nutrient (Brady and Weil, 2013).

Table 9. Chemical attributes of the soil in the area between trenches filled with topsoil, in which treatments were applied with sawdust (Covered) and without sawdust (Uncovered) in a restoring area after kaolin mining, PPSA mine, Eastern Amazon, Brazil.

Treatment	C	N	C/N	P	Al	Ca	Mg	K	CEC Total	CEC Effective	V%	m%	pH
	-------- g kg^{-1} -------			mg dm^{-3}	--------------------- $cmol_c$ dm^{-3} ------------------						%	%	H_2O
---------- 0-0.1 m ----------													
Covered	19.2^a	0.67^b	47.5^a	2.2^a	0.5^b	3.31^a	0.50^a	0.08^a	7.4^b	4.4^a	40.4^a	33.8b	4.8^b
Uncovered	20.8^a	0.84^a	20.3^b	3.0^a	0.6^a	2.98^b	0.48^a	0.07^a	7.5^a	4.2^b	32.7^b	39.7^a	5.0^a
---------- 0.1-0.2 m ----------													
Covered	5.1^b	0.38^b	13.5^b	1.3^a	0.9^a	0.69^b	0.18^b	0.04^a	3.9^b	1.8^b	20.9^a	59.5^a	4.5^b
Uncovered	14.2^a	0.69^a	20.6^a	1.5^a	0.5^b	1.82^a	0.37^a	0.04^a	5.3^a	2.8^a	35.5^b	33.2b	4.9^a
---------- 0.2-0.4 m ----------													
Covered	5.6^a	0.31^a	36.0^a	1.1^a	1.2^a	0.36^b	0.13^b	0.02^a	3.7^b	1.7^b	12.5^b	74.8^a	4.3^b
Uncovered	7.3^a	0.43^b	15.6^b	1.2^a	0.9^b	0.93^a	0.28^a	0.02^a	4.5^a	2.1^a	21.6^a	55.8^b	4.7^a

Legend: C - Carbon; N - Nitrogen; C/N – Carbon/Nitrogen ratio; P - Phosphorus; Al - Aluminum; Ca - Calcium; Mg - Magnesium; K - Potassium; SB - Sum of bases; CEC - Cation Exchange Capacity. V% - Base saturation and m% - Aluminum saturation. * Letters indicate statistical differences (Tukey's t test; $p > 0.05$).

Because they are abundant in agricultural frontier areas in the Amazon, residues from sawmills can be used in ecological restoration projects as a good alternative to cow manure, improving the soil physical and chemical conditions with increase in moisture content and values of Ca, CTC and base saturation in the more superficial layers (0.0-0.1 m) (Angst et al., 2018; Jourgholami and Abari, 2017). However, the excessive application of wood material to the soil may initially cause a reduction in N content, an essential element for plant growth and development.

When evaluating the soil's physical and chemical attributes, it is important to consider that the results are probably being influenced by the short evaluation time, since the experiment beginning. In 18 months, topsoil treatment is the most recommended, as it is the simplest and the least expensive. However, the importance of the chemical fertilization applied to the pits after covering the trenches with topsoil is emphasized, as it was used in all treatments.

2. Conclusions

Planting using topsoil and sawdust covering between planting rows favored the soil physical and chemical properties, indicating that the method of trenches is being efficient to recover degraded areas by kaolin mining. The trenches are being efficient in the ecological restoration process as well as the fast-growing tree species in the initial planting in order to create proper environmental conditions for the natural regeneration development.

The non-difference between treatments with organic matter as supplementary fertilization (topsoil, sawdust, and manure) indicated no need to incorporate external inputs of organic matter in addition to topsoil. The use of sawdust on the substrate surface triggered nutrient increases and acidity reduction in the surface layers.

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Highlights

- Trenches favored the planted and naturally established tree and shrub species
- Supplementary organic fertilization had not effect on the tree species development
- Sawdust coverage increased nutrient availability and reduced soil acidity

Tree species in initial planting achieved rapid growth and high litter produ

Supplementary Material

Annex 1. Croquis of the experiment implemented for the restoration of the post-kaolin mining area in Ipixuna-PA

28-MUR	29-PAL	
27-AMX	30-TXB	83-AMX
26-ING	31_MAR	82-MUR
25_MAR	32-AMX	81-TXB
24-AMX	33MUR	80-MAR
23-MUR	34-ING	79-ING
22-TXB	35-TXB	78-MAR
21_MAR	36-PAL	77-AMX
20-PAL	37-MAR	76-PAL
19-ING	38-PAL	75-TXB
18-PAL	39TXB	74-MUR
17-ING	40-ING	73-ING
16-TXB	41-MUR	TXB
15-AMX	42-AMX	71-PAL
14-MUR	43-ING	70-MUR
13_MAR	44-PAL	69-ING
12MUR	45-MUR	68-AMX
11-AMX	46-AMX	67-MAR
10-PAL	47-TXB	66-MAR
9-TXB	48-MAR	65-ING
8-MAR	49-MUR	64-TXB
7-ING	50-MAR	63-PAL
6-TXB	51-AMX	62-AMX
5-PAL	52-TXB	61-MUR
4-MUR	53-ING	60-PAL
3-MAR	54-PAL	59-TXB
2-ING	55-ING	58-AMX
1-AMX	56-MUR	57-MAR

T1-TOPSOIL

84-PAL	139-MUR	140-PAL
85-ING	138-TXB	141-TXB
86-MAR	137-ING	142-MAR
87-MUR	136-PAL	143-AMX
88-AMX	135-MUR	144-ING
89-TXB	134-MAR	145-ING
90-PAL	133-AMX	146-MUR
91-MAR	132-PAL	147-MAR
92-TXB	131-MUR	148-AMX
93-AMX	130-AMX	149-PAL
94-PAL	129-TXB	150-TXB
95-MUR	128-ING	151-AMX
96-ING	127-MAR	152-TXB
97-ING	126-AMX	153-ING
98-TXB	125-PAL	154-PAL
99-AMX	124-ING	155-MAR
100-MAR	123-MAR	156-MUR
101-MUR	122-MUR	157-PAL
102-PAL	121-TXB	158-MAR
103-MUR	120-PAL	159-AMX
104-ING	119-TXB	160-MUR
105-AMX	118-MUR	161-ING
106-MAR	117-MAR	162-TXB
107-TXB	116-ING	163-TXB
108-PAL	115-AMX	164-ING
109-ING	114-MUR	165-PAL
110-MAR	113-PAL	166-MAR
111-AMX	112-TXB	167-MUR

T2-TOPSOIL + SERRAGEM

195-ING	196-TXB	
194-MUR	197-PAL	250-MAR
193-AMX	198-MAR	249-AMX
192-TXB	199-ING	248-ING
191-MAR	200-TXB	247-MUR
190-PAL	201-PAL	246-ING
189-MUR	202-MUR	245-AMX
188-ING	203-MAR	244-MUR
187-AMX	204-AMX	243-PAL
186-TXB	205-PAL	242-TXB
185-ING	206-TXB	241-MAR
184-MAR	207-AMX	240-AMX
183-AMX	208-MAR	239-ING
182-PAL	209-ING	238-PAL
181-MUR	210-MUR	237-MUR
180-PAL	211-AMX	236-TXB
179-TXB	212-ING	235-MAR
178-MAR	213-MUR	234-TXB
177-MUR	214-MAR	233-PAL
176-ING	215-PAL	232-MAR
175-AMX	216-TXB	231-ING
174-MUR	217-MUR	230-AMX
173-TXB	218-AMX	229-MUR
172-ING	219-ING	228-MAR
171-MAR	220-MAR	227-AMX
170-PAL	221-PAL	226-MUR
169-AMX	222-TXB	225-ING
168-AMX	223-PAL	224-TXB

T3-TOPSOIL + ESTERCO

Legend: AMX (Ameixa - Syzygium cumini), ING (Ingá - Inga edulis), MAR (Maravuvuia - Croton matourensis), MUR (Muruci - Byrsonima spicata), PAL (Palheteira - Clitoria fairchildiana) and TXB (Taxi Branco - Tachigali vulgaris).

Table S 1. Soil density (Sd), total porosity (Tp), Macroporosity (Ma), Microporosity (Mi) and available Water content (Wc) in soil built under planting of seedlings and with application of fertilizer treatment in the pits: Topsoil only (Topsoil), Topsoil + sawdus (Sawdust) and Topsoil + bovine manure (Manure), PPSA mine, Eastern Amazon, Brazil.

	Sd	Tp	Ma	Mi	Wc
	Kg.dm^{-3}	---------------------------m^3 m^{-3}------------------------			
	---------------------------------0-10 cm --------------------------------				
Topsoil	1.26 a	0.45 a	0.17 a	0.28 a	0.079 a
Sawdust	1.26 a	0.46 a	0.19 a	0.26 a	0.083 a
Manure	1.25 a	0.48 a	0.18 a	0.30 a	0.078 a
	---------------------------------10-20 cm --------------------------------				
Topsoil	1.25 a	0.43 a	0.15 a	0.28 a	0.079 a
Sawdust	1.27 a	0.44 a	0.19 a	0.25 a	0.081 a
Manure	1.21 a	0.46 a	0.20 a	0.26 a	0.082 a
	---------------------------------20-40 cm --------------------------------				
Topsoil	1.27 a	0.45 a	0.15 a	0.29 a	0.084 a
Sawdust	1.19 a	0.46 a	0.22 a	0.25 a	0.082 a
Manure	1.23 a	0.45 a	0.20 a	0.26 a	0.076 a

Means followed by equal letters in the columns indicate that there are no statistical differences by Tukey test (5% significance).

Table S 2. Values of soil density (Sd), particle density (Pd), total porosity (Tp), macroporosity (Ma), Microporosity (Mi), Available Water Content (Wc) in an area designed to induce Natural Regeneration in substrate with application of sawdust (Covered) and without application of sawdust (Uncovered) on the surface

	Sd	Tp	Ma	Mi	Wc
	Kg.dm^{-3}	---------------------------m^3 m^{-3}------------------------			
		---------------------------------0-10 cm --------------------------------			
Covered	1.22 a	0.47 a	0.16 a	0.31 a	0.095 a
Uncovered	1.23 a	0.47 a	0.18 a	0.29 a	0.080 b
		---------------------------------10-20 cm --------------------------------			
Covered	1.33 a	0.45 a	0.15 a	0.31 a	0.082 a
Uncovered	1.26 b	0.45 a	0.17 a	0.28 a	0.077 a
		---------------------------------20-40 cm --------------------------------			
Covered	1.39 a	0.42 a	0.11 a	0.30 a	0.082 a
Uncovered	1.39 a	0.43 a	0.12 a	0.31 a	0.075 a

Means followed by equal letters in the columns indicate that there are no statistical differences by t test (5% significance).

DISCUSSÕES GERAIS (CAPÍTULO V)

Esta tese avalia o potencial de restauração na Amazônia brasileira, divididos em três publicações cientificas. Foram avaliados dois municípios paraenses (Paragominas e Ipixuna do Pará) com grande expressão na economia do estado do Pará. Entretanto, são necessárias aplicações de políticas públicas e ações que revertam o cenário de degradação ambiental na região e que fomentem a implementação de áreas prioritárias para restauração e conservação pode ser o estágio inicial nesse processo (**Capítulo 2**). Paragominas com um histórico de forte desmatamento, foi um dos municípios que mais desmatou e degradou o meio ambiente na Amazônia. Atualmente Paragominas é um modelo na eficiência de ações ambientais com o título de "Município Verde", o que resultou na saída da lista vermelha nacional dos municípios que mais desmatam no país. A preocupação com a perda da vegetação é mundial, assim como seus efeitos e ações para reverter esse cenário vem sendo discutido, como o de restaurar 350 milhões de hectares até 2030 (GUERRA et al., 2020). A metodologia a ser aplicada a cada especificidade na busca da eficiência não é tarefa fácil, como é o caso da mineração. Essa atividade pode causar a desestruturação do solo (COURT et al., 2018; DUDLEY et al., 2018), fator esse, desafiador, tanto quanto implementar metodologias eficientes na priorização de características ecológicas (**Capítulo 3**) e edáficas (**Capítulo 4**).

1.1. Importância do uso racional dos recursos florestais na Amazônia

A Amazônia possui a maior reserva de biodiversidade do planeta, onde ainda não se dispõe do conhecimento de todas as espécies existentes, nem sua real distribuição geográfica (TER STEEGE et al., 2013). Entretanto, todo esse potencial vem sendo ameaçado por ações antrópicas (KINDERMANN et al., 2008; HANSEN et al., 2013). Segundo Feeley & Silman (2009), por exemplo, a previsão é que até 2050, cerca de 12-24% das espécies arbóreas amazônicas terão seu habitat reduzido, resultando em cerca de 5-9% de espécies comprometidas à extinção, não somente pela perda de habitat, mas também pelas mudanças de uso da terra. Atualmente os impactos já podem ser sentidos como a perda da biodiversidade, redução na quantidade e qualidade da água, mudanças no ciclo hidrológico, alterações na atmosfera em decorrência da emissão descontrolada de gases provenientes do desmatamento e perda de oportunidades para o uso econômico sustentável da floresta (FEARNSIDE, 2006; ANDRADE & ROMEIRO, 2011).

Um das regiões Amazônicas que vem sofrendo ao longo dos anos com as mudanças no uso e cobertura é o estado do Pará, que apresenta um dos maiores índices de desmatamento da Amazônia (INPE, 2019). Seu território é composto por 55% de Unidades de Conservação, terras indígenas e/ou áreas militares (NUNES et al., 2017). Apesar de possuir mais da metade do seu território protegido, sua economia é voltada a indústria extrativista, agricultura e pecuária, as quais fomenta a abertura de grandes áreas para implantação dos empreendimentos.

O desmatamento pode inviabilizar legalmente o desenvolvimento econômico de uma região, o que vem resultando ao longo dos anos em políticas a favor do meio ambiente, tal como o Decreto n º 6321, de 21 de dezembro de 2007. Um município que desmata acima do permitido por ano é impossibilitado de acessar os créditos de financiamento disponibilizados pelo governo, pois entra em uma lista vermelha do Ministério do Meio Ambiente (MMA), além de ser obrigado a recuperar a área desmatada (Lei nº 12.651/2012). Por lei, o proprietário que desmatada acima do permitido, deve por obrigação legal recompor a área desmatada, e assim cumprir com Lei de Proteção da Vegetação Nativa (Lei nº 12.651/2012).

1.2. Município de Paragominas: de degradador a município verde

O crescimento populacional e o dinamismo econômico para alavancar a mudança do título de município degradador para município verde em Paragominas teve origem após o intenso processo de degradação **(Capítulo 2 – Figura 4)**. O surgimento da preocupação social com meio ambiente, foi incentivado por ações para o desenvolvimento de técnicas e planejamento ambiental adequado à realidade local, aliado às exigências do mercado consumidor. Uma das alternativas é a utilização de ferramentas de geotecnologias aplicadas no mapeamento de áreas prioritárias para a conservação e/ou restauração, que orienta na tomada de decisão dos processos ecológicos (FRANCISCO; et al., 2007; **Capítulo 2 - Figura 3, 4 e 5**) e, também no monitoramento, mapeamento e a gestão da paisagem de uma forma integrada entre propriedades.

O levantamento de áreas prioritárias para a conservação é o primeiro passo no diagnóstico ambiental do município, diferenciando os tipos de uso do solo, graus de degradação e diferentes metodologias a serem aplicadas para a sua recuperação. Ao avaliar a situação atual de Paragominas **(Capítulo 2)**, foram identificadas 369 propriedades rurais com passivos ambientais em sete categorias de uso do solo, onde 79 delas foram desmatadas, com degradação de áreas de preservação permanente (APP) após 2008 que, segundo o Código Florestal Brasileiro, devem ser recuperadas. Nesse cenário, uma das alternativas viáveis quando se estuda um território, são possibilidades de interligações de fragmentos florestais, áreas de preservação permanente entre propriedades, podendo ser incentivada pela manutenção da reserva legal, formando corredores ecológicos **(**ALMEIDA et al., 2011; **Figura 3 – Capítulo 2)**.

Segundo Sistema Nacional de Unidades de Conservação da Natureza (SNUC), corredores ecológicos são definidos como “porções de ecossistemas naturais ou seminaturais, ligando unidades de conservação (UC), que possibilitam entre elas o fluxo de genes e o movimento da biota, facilitando a dispersão de espécies e a recolonização de áreas degradadas, bem como a manutenção de populações que demandam para sua sobrevivência áreas com extensão maior do que aquela das unidades individuais” **(Capítulo 2 – Figura 2)**. Esse conceito não se restringe à UCs, mas também em fragmentos florestais que favorecem o fluxo de animais e sementes, e as atividades de reflorestamento que são estratégias para a conservação da biodiversidade em paisagens fragmentadas (ALMEIDA et al., 2011).

1.2. Desafio da restauração florestal em área de mineração

O Brasil é segundo maior produtor mundial de minério e o estado do Pará é uma região de forte atividade no setor. Em 2018, 88% das exportações do estado destinavam-se às indústrias de mineração e transformação mineral (SINMINERAL, 2019). Dentre os minérios disponíveis no Pará, a bauxita e o caulim são explorados em Paragominas e Ipixuna do Pará, municípios vizinhos do nordeste paraense, ambos com metodologia de lavra a céu aberto, com supressão de vastas áreas de floresta nativa. Isto tudo requer medidas de mitigação e controle ambiental, bem como a implementação de processos de recuperação das áreas outrora degradadas.

A restauração após mineração deve levar em consideração vários atributos, dentre os quais uma lista de espécies de ocorrência no ecossistema de referência (SALOMÃO et al., 2012). O método de restauração a ser aplicado depende de várias especificidades locais e tipo de degradação, onde a premissa é o estabelecimento de uma metodologia eficiente, independentemente do método, com rápido recobrimento do solo, retorno das funções ecológicas e uma estabilidade dos indivíduos arbóreos ao longo dos anos, e que resultem em menores perdas e custos (SALOMÃO et al., 2013). Restaurar área minerada não é tarefa fácil, visto que há uma desestruturação dos perfis do solo, compactação do terreno, erosão e lixiviação em virtude de erros no nivelamento das áreas **(Capítulo 3 e 4)**.

Na reconformação topográfica, devido ao manuseio de equipamentos há uma limitação física pela compactação do solo. Isto resulta em baixos teores de matéria orgânica e nutrientes em virtude da alta taxa de oxidação, prejudicando o desenvolvimento radicular e levando a posterior tombamento de indivíduos arbóreos (SOUZA, 2018). Nesse sentido, os **Capítulos 3 e 4** retratam os resultados de uma nova metodologia com a abertura de trincheiras desenvolvido pela Embrapa para a restauração de áreas degradas por mineração de caulim. A abertura de trincheiras em projetos de restauração é algo novo. A metodologia é baseada no favorecimento do desenvolvimento radicular das espécies florestais, visto que na atividade de mineração a céu aberto, há uma grande desestruturação dos horizontes do solo. No entanto, foi observado por meio de análises físico-químicas do solo, que com 18 meses de acompanhamento as transformações físico-químicas do solo são ainda muito recentes e os resultados não diferenciaram nos três tratamentos propostos com as adubações orgânicas no fundo de cova. Porém, as adubações e a trincheira beneficiaram o desenvolvimento dos indivíduos arbóreos quando comparados a outros estudos de restauração em área de mineração. A mortalidade de 2,4% foi altamente satisfatória, com alta cobertura de copa dos indivíduos plantados (85,71%) (SALOMÃO et al., 2007; SALOMÃO et al., 2014; RIBEIRO et al., 2019; **Capítulo 3)**.

Além do favorecimento do desenvolvimento radicular pela aplicação das trincheiras, a adubação orgânica foi utilizada em virtude de sua eficiência nas propriedades químicas e físicas do solo **(Capítulo 4)**. A adubação orgânica foi facilitada devido à sua grande disponibilidade no município de Ipixuna, que tem em sua economia o beneficiamento de madeira (serrarias) e a pecuária, com grande disponibilidade de pó de serragem e esterco bovino **(Capítulo 3)**. Para a realidade da mineração, com extensas áreas a se recuperar anualmente, se faz necessário uma avaliação de custo para validar a metodologia proposta, além de ser uma alternativa a ser proposta ao município para ser utilizada na recuperação das áreas degradadas. Por fim, é importante incentivar ações de restauração aliado as atividades de gestão e políticas públicas que fomentem a conectividade dos fragmentos dentro das propriedades rurais nos municípios da Amazônia (**Capítulo 2).**

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CONSIDERAÇÕES FINAIS (CAPÍTULO VI)

Este capítulo relata as principais conclusões desta Tese, por meio dos estudos provenientes dos **capítulos 2, 3 e 4** (artigos científicos), elabora para responder o objetivo geral do estudo aqui apresentado: Considerando a situação atual da Amazônia com relação à perda da vegetação original e a necessidade de restaurar essas áreas, foi avaliado o potencial de restauração florestal na Amazônia brasileira, com enfoque na região do nordeste paraense, para propor métodos de restauração eficientes para a realidade da mineração.

A Amazônia possui o maior remanescente florestal tropical do mundo, com 5,2 milhões de km² (61% do território do país), com milhões de espécies de fauna e flora e detentora de uma das maiores reservas de água doce do planeta. Com toda essa riqueza e disponibilidade de recursos, ainda é alvo de displicência pela ausência de gestão e preocupação de grande parte de empresários e políticos. Os incentivos governamentais ao desenvolvimento da economia ao longo dos anos, sem previamente ser estudado seus impactos e as consequências refletidas mundialmente, tal como as mudanças climáticas e o aumento da camada de ozônio. Não se atentar para a sustentabilidade ambiental e o ecossistema global acarretou impactos que, por vezes são irreversíveis.

Retrato desse incentivo desordenado foi sentido no município de Paragominas que, devido ao acelerado crescimento econômico acarretou a perda de quase a metade de seu território em um período de 364 anos pelas atividades de mineração, agricultura e pecuária. Esse cenário foi retratado no **Capítulo 2**, onde foram avaliados, por meio de ferramentas de informações geográficas 522 km de rios e 904 nascentes que exigem restauração.

Com o avanço de estudos e a percepção que a preocupação ambiental com a manutenção dos serviços ecossistêmicos reflete diretamente na biodiversidade, balanço de emissões de carbono, água e solo, que é de interesse local, nacional e global vem mudando a percepção de como os incentivos devem ser pautados em análises mais eficientes. Uma das alternativas para sanar o passivo ambiental do município de Paragominas é o incentivo da recomposição de reserva legal das propriedades e a restauração de áreas de preservação permanentes (APP), requisitos legais que proprietários são obrigados a cumprir, pois refletem na busca de incentivos financeiros e exportação de seus produtos (**capítulo 2**). Nesse sentido, olhando para a resolução do passivo e práticas sustentáveis, o favorecimento de corredores ecológicos conectando remanescentes de fragmentos florestais a fim de auxiliar a melhoria das condições ecológicas e conservação da diversidade biológica, aliado a práticas conservacionistas e educação ambiental para que a população adquira consciência ambiental na valorização e engajamento na defesa da conservação é uma opção viável e sustentável.

O levantamento de áreas prioritárias é uma opção de gestão planejada e participativa que pode ser utilizada para outros municípios de forma a tratar os passivos ambientais de forma integrada, com a visão global da manutenção dos serviços ecossistêmicos, confirmando a hipótese do **Capítulo 2**.

Propor metodologias eficientes para cada especificidade de impacto, características locais e diferentes biomas são tarefas desafiadoras e, quando se trata de mineração, ainda há um agravante maior em virtude da desestruturação dos horizontes e compactação do solo. Em virtude dessa característica relevante, que foi desenvolvido o experimento pensando no favorecimento do desenvolvimento radicular das espécies arbóreas e consequentemente o recobrimento do solo para estabelecendo um microclima favorável, utilizando diferentes adubações orgânicas disponíveis no município e a abertura de trincheiras. No caso de Ipixuna, que possui impactos semelhantes ao de Paragominas e com grande oferta de insumos como esterco bovino e serragem, que por vezes possui uma dificuldade de destinação final, a utilização da serragem em áreas de restauração também pode solucionar um dos entraves da destinação desse resíduo no município (**Capitulo 3 e 4**).

Nesse estudo (**Capítulos 3 e 4**) foi concluído que a utilização de trincheiras favoreceu o recobrimento do solo e desenvolvimento da vegetação, sendo que para a vegetação, o tratamento topsoil foi o que apresentou os melhores resultados, porém em relação ao solo, a serragem favoreceu as propriedades físicas e químicas, indicando que os métodos utilizados estão sendo eficientes na recuperação de área minerada após 18 meses, além de favorecer o processo de restauração ecológica e ambiente favorável à regeneração natural, rejeitando as hipóteses inicial do estudo, no qual o esterco bovino apresentaria melhores resultados.

Apesar do período curto de análise, os resultados foram satisfatórios e promissores no que se refere a realidade da mineração, entretanto é necessário a continuidade do monitoramento para validação de sua eficiência durante o processo de sucessão florestal, além da avaliação de custo ao longo dos anos comparados aos métodos já desenvolvidos para essa realidade.