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**MANEJO INTEGRADO DE ESPÉCIES INVASORAS EM ÁREAS
MINERADAS EM PROCESSO DE RECUPERAÇÃO**

Belém
2026

ARIANNE FLEXA DE CASTRO

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MINERADAS EM PROCESSO DE RECUPERAÇÃO**

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de Recuperação**

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MANEJO INTEGRADO DE ESPÉCIES INVASORAS EM ÁREAS MINERADAS EM PROCESSO DE RECUPERAÇÃO

RESUMO

A recuperação ambiental tem como objetivo restituir a biodiversidade, bem como as funções e os serviços ecossistêmicos perdidos em decorrência de impactos ambientais. Nessas áreas, a presença de espécies vegetais invasoras, espécies exóticas de rápido estabelecimento e expansão, constitui uma das principais barreiras ao sucesso da recuperação a longo prazo, uma vez que impacta negativamente o ambiente e dificulta o estabelecimento das comunidades nativas. A utilização de estratégias de manejo que integrem hipóteses ecológicas e ferramentas de sensoriamento remoto apresenta grande potencial para aprimorar as práticas de monitoramento e gestão ambiental, especialmente a partir da compreensão dos fatores bióticos e abióticos que determinam o sucesso da invasão. Assim, este trabalho teve como objetivo auxiliar no manejo integrado para o controle de espécies invasoras em áreas de recuperação ambiental, com foco em regiões impactadas pela mineração em Carajás, Pará, Brasil. Para alcançar esse objetivo, a pesquisa concentrou-se em duas espécies invasoras comuns na região, *Melinis minutiflora* Baeuv. e *Muntingia calabura* L. Foram investigados fatores como a fertilização do solo e os impactos dessas espécies sobre as comunidades residentes nativas, visando ampliar a compreensão de métodos eficazes de manejo, com ênfase na redução do estabelecimento e da propagação de espécies invasoras. Adicionalmente, foi desenvolvida uma abordagem aplicada para a implementação de um sistema de monitoramento remoto das populações invasoras, capaz de detectar essas espécies em tempo quase real e em larga escala, a partir de imagens obtidas por veículos aéreos não tripulados. Os resultados evidenciaram o papel das condições abióticas, notadamente a fertilização, como facilitadora da invasão, promovendo o crescimento da espécie invasora *M. minutiflora* em detrimento das espécies nativas. Em nível de comunidade, observou-se um processo de homogeneização funcional em áreas de recuperação invadidas por *M. calabura*, associado à redução da riqueza funcional e a alterações na composição funcional das comunidades. Por fim, a aplicação da metodologia automatizável baseada em aprendizado de máquina demonstrou alta eficiência na detecção da *M. calabura*, gerando mapas preditivos com elevada acurácia, baixos erros e alto poder de segmentação. Em conjunto, esses resultados fornecem subsídios importantes para a tomada de decisão no direcionamento de esforços de manejo, especialmente relacionados à preparação do solo, ao plantio de enriquecimento e ao monitoramento de longo prazo das populações invasoras, etapas essenciais para o sucesso da recuperação ambiental.

Palavras-chave: Aprendizado profundo, ecologia funcional, invasão biológica, recuperação ambiental, sensoriamento remoto

INTEGRATED MANAGEMENT OF INVASIVE SPECIES IN MINED AREAS UNDERGOING REHABILITATION

ABSTRACT

Environmental rehabilitation aims to reestablish biodiversity as well as the ecosystem functions and services lost as a result of environmental impacts. In these areas, the presence of invasive plant species, exotic species characterized by rapid establishment and spread, represents one of the main barriers to long-term rehabilitation success, as they negatively affect the environment and hinder the establishment of native communities. The use of management strategies that integrate ecological hypotheses with remote sensing tools has great potential to improve monitoring and environmental management practices, particularly through a better understanding of the biotic and abiotic factors that determine invasion success. Accordingly, this study aimed to develop an integrated management approach for the control of invasive species in areas undergoing environmental rehabilitation, focusing on regions impacted by mining activities in Carajás, Pará, Brazil. To achieve this objective, the research focused on two invasive species commonly found in the region, *Melinis minutiflora* Baeuv. and *Muntingia calabura* L. Factors such as soil fertilization and the impacts of these species on native communities were investigated in order to improve the understanding of effective management methods, with an emphasis on reducing the establishment and spread of invasive species. In addition, an applied approach was developed to implement a remote monitoring system for invasive populations, capable of detecting these species in near real time and at large spatial scales using imagery acquired by unmanned aerial vehicles. The results highlighted the role of abiotic conditions, notably fertilizers, as facilitators of invasion, promoting the growth of the invasive species *M. minutiflora* at the expense of native species. At the community level, a process of functional homogenization was observed in rehabilitated areas invaded by *M. calabura*, associated with a reduction in functional richness and changes in the functional composition of communities. Finally, the application of an automated machine-learning-based methodology showed high efficiency in detecting the occurrence of *M. calabura*, generating predictive maps with high accuracy, low error rates, and strong segmentation performance. Together, these results provide important support for decision-making in guiding management efforts, particularly those related to soil preparation, enrichment planting, and long-term monitoring of invasive populations, key steps for achieving successful environmental restoration.

Keywords: Biological invasion, deep learning, environmental rehabilitation, functional ecology, remote sensing

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1. INTRODUÇÃO GERAL

O Brasil estabeleceu a meta de restaurar 12 milhões de hectares até 2030 (Brasil, 2017) com objetivo de restabelecer a biodiversidade e os serviços ecossistêmicos a níveis próximos aos pré-distúrbio a partir recuperação de áreas degradadas (RAD) (Gastauer et al., 2018). No entanto, a recuperação ambiental efetiva enfrenta grandes desafios, sendo a presença de espécies invasoras uma das principais barreiras (Weidlich et al., 2020a). Definidas como espécies exóticas capazes de se estabelecer, expandir e dispersar rapidamente, as invasoras impactam a biodiversidade, alteram os ciclos de nutrientes, água e fogo, além de dificultar o estabelecimento de espécies nativas e prejudicar o avanço sucessional durante a RAD (Blackburn et al., 2011; Levine et al., 2003; Pyšek et al., 2020). Apesar da urgência no combate a essas espécies, a eficácia das ações a longo prazo ainda é limitada (Castro et al., 2024; Young et al., 2020), principalmente devido à falta de um manejo consolidado para reduzir sua competitividade e aos custos e riscos operacionais associados ao monitoramento em larga escala (Weidlich et al., 2020b). Diante desse cenário, estratégias de controle são essenciais, incluindo a manipulação das condições abióticas, ajustes na composição da comunidade residente, métodos diretos de combate (como capina manual ou química) e monitoramento contínuo, garantindo a maior eficácia no combate às invasoras.

O manejo em RAD visa acelerar a cobertura vegetal e restaurar funções ecossistêmicas, frequentemente por meio de práticas como fertilização para estimular o crescimento das espécies. Embora o aumento da disponibilidade de nutrientes seja essencial para o desenvolvimento da vegetação, pode gerar efeitos indesejáveis em áreas suscetíveis à invasão biológica (Knauf et al., 2021; Ostertag & Verville, 2002). Nos estágios iniciais da recuperação, o excesso de recursos não assimilado pelas espécies nativas pode favorecer espécies invasoras, que geralmente apresentam altas taxas de aquisição e uso eficiente de recursos (Davis, Grime & Thompson, 2000; Caldeiras et al., 2021; Funk et al., 2008). Nesse contexto, espécies pioneiras são fundamentais na RAD, amenizando condições ambientais adversas e aumentando a resistência à invasão ao reduzir recursos disponíveis para espécies invasoras (Yu et al., 2020). Assim, compreender os efeitos da fertilização sobre o crescimento de espécies nativas e suas interações com invasoras é crucial para orientar protocolos de manejo e recuperação.

As interações ecológicas desempenham papel central no sucesso da RAD e na suscetibilidade à invasão em ambientes manejados. A abordagem funcional, baseada em traços morfológicos, anatômicos e fisiológicos das espécies, permite investigar como plantas capturam e utilizam recursos como luz, água e nutrientes, além de revelar diferentes estratégias

adaptativas (Kattge et al., 2011; Fried et al., 2019; Funk, 2016; Gundale et al., 2024; Hu et al., 2019). Espécies invasoras podem apresentar diferentes estratégias funcionais, incluindo rápido crescimento, alta eficiência no uso de recursos ou maior tolerância a estresses ambientais. A análise funcional da competição permite identificar quais combinações desses traços estão associadas ao sucesso invasor (Fagúndez & Lema, 2019). Essa abordagem permite compreender como as características das espécies influenciam a exploração de recursos, o funcionamento do ecossistema e a organização das comunidades (Funk; W., 2016; Gundale et al., 2024; Hu et al., 2019).

Diferenças funcionais entre espécies invasoras e comunidades nativas também ajudam a avaliar como fatores ecológicos, como recursos, distúrbios e condições locais, influenciam a diversidade e a estrutura funcional das comunidades invadidas (Fried et al., 2019; Kaushik et al., 2022). Além disso, possibilita investigar os impactos da invasão, incluindo processos de homogeneização funcional (Funk et al., 2008; Carboni et al., 2018; Bando et al., 2023). Espécies invasoras podem adotar estratégias de convergência funcional com a comunidade residente (“join-the-locals”), especialmente em ambientes com recursos limitantes, estabelecendo-se por meio da similaridade funcional e da sobreposição no espaço de nicho com espécies nativas (Pearson et al., 2018; Tecco et al., 2010; Yi et al., 2025). Isso pode afetar a resiliência e alterar processos ecológicos, uma vez que mudanças na abundância e perdas de espécies com traços originais pode reduzir a complementaridade de nicho (Wong & Dowd, 2021; Bando et al., 2023). Assim, para aumentar a resistência biótica, reduzir a homogeneização funcional e restaurar a resiliência de ecossistemas invadidos, é necessário compreender essas estratégias e identificar espécies ou grupos funcionais prioritários para o enriquecimento (Carboni et al., 2018).

Uma vez que as ações de manejo estejam estabelecidas, o monitoramento contínuo das populações e a detecção precoce de novas ocorrências se tornam fundamentais para o sucesso dos projetos de RAD (Sankaran et al. 2023; Tataridas et al., 2022). Na prática, essa etapa é desafiadora uma vez que o acompanhamento em larga escala em intervalos satisfatórios se torna impraticável, especialmente em áreas remotas e de difícil acesso. Tecnologias como UAVs (Veículos Aéreos Não-Tripulados) e sensoriamento remoto têm se mostrado promissoras, permitindo avaliação periódica e detecção quase em tempo real de espécies invasoras (Asner et al., 2008; Bradley, 2013; Fricke & Olden, 2023). O aprendizado profundo, ramo do aprendizado de máquina, vem sendo aplicado no processamento de imagens para identificar padrões complexos e características discriminantes das espécies, facilitando o mapeamento e monitoramento ambiental (Chollet & Allaire, 2018; Kattenborn et al., 2021; Dash et al., 2019; Yuan et al., 2020). Juntos, esses avanços permitem a avaliação periódica capaz de detectar essas

espécies em tempo quase real e em larga escala, e têm sido cada vez mais utilizados no monitoramento ambiental (Asner et al., 2008; Bradley, 2013; Fricke & Olden, 2023). Tais abordagens geram mapas que permitem detecção precoce, identificação de áreas de alta ocorrência e avaliação temporal das ações de manejo (James & Bradshaw Massetti et al., 2023).

Diante do apresentado, este trabalho teve como objetivo auxiliar no manejo integrado para o combate a espécies invasoras em RAD, com foco nas regiões impactadas pela mineração em Carajás, PA, Brasil. Para alcançar esses objetivos, a pesquisa teve foco em duas espécies invasoras comuns na região, a gramínea *Melinis minutiflora* Baeuv. e a espécie arbustiva *Muntingia calabura* L. A pesquisa abordou três aspectos complementares: (i) efeitos da fertilização sobre o crescimento de espécies nativas e interações com invasoras (Sessão I), (ii) impactos funcionais da invasão sobre as comunidades nativas (Sessão II), e (iii) desenvolvimento de um sistema de monitoramento remoto capaz de detectar as espécies em larga escala e quase em tempo real a partir de imagens de UAV (Sessão III). Conjuntamente, os estudos buscam avançar na compreensão das estratégias de manejo, fornecendo métricas e ferramentas aplicáveis para apoiar gestores e órgãos ambientais em projetos de recuperação ambiental.

2. OBJETIVO GERAL

Auxiliar no manejo integrado para o combate a espécies invasoras em RAD, com foco nas regiões impactadas pela mineração em Carajás, PA, Brasil.

2.1 OBJETIVOS ESPECÍFICOS

- Avaliar a influência de diferentes substratos e níveis de fertilização nas interações bióticas entre gramíneas nativas da Amazônia Oriental e a gramínea invasora *Melinis minutiflora* P. Beauv., visando fornecer subsídios para a recuperação de áreas degradadas mineradas na região (Sessão I)
- Avaliar como a espécie invasora *Muntingia calabura* L. afeta a funcionalidade das comunidades nativas remanescentes em áreas em recuperação fornecendo subsídios para estratégias de manejo e restauração. (Sessão II)
- Aplicar uma metodologia automatizada para a classificação da espécie invasora *Muntingia calabura* L. (Muntingiaceae) em áreas de recuperação ambiental na região de Carajás, Amazônia Oriental, por meio da análise de imagens de alta resolução e segmentação via redes neurais convolucionais. (Sessão III)

3. SESSÃO I

Fertilization during mineland rehabilitation may shift the competitive outcomes towards invasive species

A primeira sessão desta tese já foi aceita e publicada na revista Restoration Ecology, DOI: 10.1111/rec.14108. A sessão foi elaborada e formatada conforme as normas da publicação científica disponível em:

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Fertilization during mineland rehabilitation may shift the competitive outcomes towards invasive species

ABSTRACT

Managing invasive species is essential for achieving mineland rehabilitation goals and ensuring the long-term provision of critical ecosystem services while preventing new dispersion sources to neighboring areas. Traditional techniques include chemical and manual weeding, but frequent reinvasion limits their long-term success. Therefore, additional integrated tools, such as stimulating natural competitors, may become necessary, especially where sensitive ecosystems, e.g. the ferruginous savanna ecosystem (*cangas*) from the Carajás National Forest, Eastern Amazon, Brazil, are found nearby rehabilitation sites. Here, we investigate the influence of different substrates and fertilization levels on the biotic interactions between two native *canga* grasses (*Axonopus longispicus* and *Paspalum cinerascens*) and the invasive molasses grass (*Melinis minutiflora*), which is frequently found in anthropized and natural ecosystems in Latin America. Nutrient application significantly influenced the growth, resource use strategies, and competitive outcomes of *M. minutiflora*. Nutrient application has positive effects on the growth of native species when cultivated in isolation but reduces plant development when subjected to competition with molasses grass, potentiating the invader. Although neither of the tested native species exhibited competitive advantages over *M. minutiflora*, increased nitrogen availability favored the competitive ability of this invasive grass. Thus, eliminating fertilization during mineland rehabilitation may be important for reducing the cover of *M. minutiflora* in the Carajás region, as sensitive *canga* ecosystems lack natural barriers against invasion. This strategic approach mitigates the operational risks and costs associated with combating invasive species from rehabilitating minelands, reducing propagule pressure on neighboring *canga* areas.

Key words: *canga* ecosystems, Carajás National Forest, interspecific competition, invasion management, *Melinis minutiflora*, resource use

Implications for Practice

- As sensitive ecosystems such as *cangas* from the Carajás National Forest may lack natural barriers against invasive species, we highlight the importance of invasive species management at neighboring sites, including rehabilitation areas, for reducing propagule pressure.
- As no effective native competitor for aggressive molasses grass was found, manual or chemical weeding remains the method of choice to manage this aggressive invasive species in natural ecosystems and mineland sites.
- Refraining from nitrogen fertilization optimizes mineland rehabilitation success, as no fertilization maximizes native vegetation cover while simultaneously minimizing invasive growth, thus reducing spread and invasive propagule pressure on neighboring sites

3.1 Introduction

Invasive plants are among the main threats to habitats and biodiversity worldwide (Carboni et al.2021) and represent one of the most critical barriers to rehabilitation projects (Linderset al.2019; Weidlich et al.2020a). The degree of invasiveness and site vulnerability depends on several factors, including propagule pressure, environmental conditions (e.g. microclimate, slope, exposure, and soil properties), and interactions with native communities, such as shading or competition (Catford et al.2019). Greater phenotypic variability and wider ecological niches compared to most native species (Funk et al.2008; Schlaepfer et al.2009) allow invasive species to efficiently establish in degraded environments (Marin et al.2020), where they hinder the development of native vegetation. Moreover, established populations of invasive species have become a source of seed dispersion, posing threats to adjacent native ecosystems and rehabilitation activities (Gioria et al.2019; Dairel & Fidelis2020; Xavier et al.2021). Thus, managing invasive species is a priority for achieving restoration or rehabilitation goals, guaranteeing key ecosystem services, and reducing threats to neighboring sites in the long term (e.g. Gann et al.2019; Gastauer et al.2021; Castro et al.2023).

The success of most invasive species in rehabilitation areas can be attributed to their wider ecological niches and adaptability to environmental changes, which are reflected in their phenotypic variability (Ribeiro et al.2017). This enables them to capitalize on fluctuations in resources, especially in degraded environments, as highlighted by Zhang et al. (2022). In these contexts, invasive species thrive by effectively exploiting unused resources, either through niche opportunities or by out-competing weaker competitors via competitive exclusion (Davis et al.2000; Mathakutha et al.2019; Carboni et al.2021). Competitive strategies involve resource uptake and allocation, impacting plant performance in terms of biomass production, photosynthesis, and water and nutrient use (Richards et al.2006; Gioria & Osborne2014). Species interactions, such as those involving nitrogen-fixing bacteria and mycorrhizae, can impact nutrient availability and species coexistence (Chunget al.2023). Understanding nitrogen exploitation strategies through tools such as nitrogen-stable isotopes and leaf nitrogen (Dawson et al.2002; Craine et al.2015; Sena-Souza et al.2023) can provide important insights for managing competition between species, including native and invasive species. More-over, water and light availability play crucial roles in plant development, influencing adaptive responses such as biomass allocation, investment in leaf area, and rates of gas exchange and photosynthesis to optimize growth and development (Kunstler et al.2016). Such adaptations

influence survival, inter-actions with neighbors, and the outcomes of competition (Barger et al.2003; Eller & Oliveira 2017; Yannelli et al.2017; Bueno et al.2019).

Traditional rehabilitation management involves the planting or seeding of species (e.g. Ramos et al.2019; Caldeira et al.2021; Maciel et al.2023; Boanares et al.2023; Massante et al.2023) and relies on fertilization to maximize vegetation growth. This procedure frequently confronts challenges from invasive species infiltrating early in the rehabilitation process (Weidlich et al.2020b; Torres et al.2021), and control measures for invasive species, such as chemical and manual weeding, often demonstrate limited long-term success due to reinvasion (Pearson et al.2016; Weidlich et al.2020a). The integrated management of rehabilitation sites, including the selection of native species able to compete with invasive species and the optimization of resource management, may enhance the effectiveness of traditional techniques for controlling invasive species and increasing rehabilitation outcomes (Funk et al.2008). For the adequate management of the environment, it is crucial to understand the factors that promote invasion and increase community resistance, emphasizing the importance of detailed knowledge regarding resource demands and competitive abilities among natives to outcompete invasive plants (Schuster et al.2018).

Here, we investigated the influence of different substrates and fertilization levels on the biotic interactions between grasses (Poaceae) native to the Eastern Amazon, recently recognized as promising for mineland rehabilitation activities in the region (Caldeira et al.2021), and invasive molasses grass (*Melinis minutiflora* P. Beauv.). The native grasses are *Axonopus longispicus* (Döll), *Kuhlmannia* (Poaceae), and *Paspalum cinerascens* (Döll) A.G. Burm. & C.N. Bastos. We used soils from natural ecosystems and mineland rehabilitation sites to determine whether both native species can outcompete the invasive species and whether the addition of fertilizer to mineland rehabilitation substrates changes the results of competition interactions. We furthermore analyzed the influence of substrates, fertilization, and competition on niche overlap and the functional space occupied by the three species. We expect that (1) invasive *M. minutiflora* plants would be favored by nutrient applications and inhibit the growth of native species due to increased resource use efficiency, that (2) native species could outperform invasive grasses in nonfertilized treatments due to their adaptation to limiting environmental conditions and that (3) the invasive species is characterized by more acquisitive traits, especially in fertilized treatments, than native species. This study aims to contribute valuable insights into the ecological dynamics between native and invasive species, with implications for the selection of appropriate management strategies in rehabilitation projects.

3.2 Methods

3.2.1 Geographic Setting

The study was carried out in a greenhouse using species and substrates from the Carajás National Forests, PA-Brazil (Fig.S1). The climate of the region is defined as Aw, hot, and tropical humid according to the Koppen classification (Alvares et al.2013), with a mean temperature above 25°C. The mean annual precipitation is 2300 mm, with a rainy season occurring between November and April, a dry period occurring between June and September, and short transition periods in May and October.

The Carajás National Forest is a category IV conservation unit of approximately 4120 km². The original vegetation of this region is dominated by open and dense rainforests, but iron stone outcrops cap large reserves of iron ore and occupy 115.8 km² of the landscape (Souza-Filho et al. 2016). Additionally, known as cangas, the distinctive edaphic conditions of these environments led to high levels of endemism with groups of highly diversified species (Giulietti et al. 2019).

Further elements of the landscape are open cast mines, which are mainly related to iron ore extraction. Here, the inertial over-burden not used during the extraction process is deposited, which results in the formation of large waste piles. The environmental rehabilitation of mine pits and waste piles aims to reduce the environmental impact, guarantee slope stabilization and protect soil against erosion (Gastauer et al. 2022; Castro et al. 2023). For that purpose, slopes are hydroseeded using a mixture of soil amendments (i.e. fertilizers, organic matter, and mulch). Species mixtures currently applied contain commercial fast-growing legumes and grasses, which are able to achieve rapid vegetation cover that trigger the rehabilitation process (Cristina & Gomes 2013; Silva et al. 2018; Gastauer et al. 2022). To increase the environmental performance of rehabilitating areas, additional native species have been explored for this purpose (Gastauer et al. 2020). Due to their high abundance in canga ecosystems and high biomass production, the grasses *Axonopus longispicus* and *Paspalum cinerascens* (Viana et al.2016) have been indicated as suitable candidates for rehabilitation efforts (Caldeira et al.2021; Boanares et al. 2023).

Spontaneous establishment of invasive species was observed in natural, disturbed, and rehabilitating environments in the Carajás National Forest (Mota et al. 2018). Among them, *Melinis minutiflora* forms large populations in waste piles, and occurrences of this species are found in canga ecosystems (Fig.S1). Originally from Africa, this molasses grass is considered

an aggressive invasive species in degraded sites from different neotropical biomes (Barger et al. 2003; Ribeiro et al. 2017; Zenni et al. 2018) due to its high biomass production, monodominant stand formation (Hoffmann et al. 2004), nutrient cycling changes, fire occurrence increases, and high dominance in the soil seed bank (Hoffmann & Haridasan 2008; Dairel & Fidelis 2020; Xavier et al. 2021). In waste piles, the dominance of *M. minutiflora* hinders the establishment of native species, delaying the rehabilitation process (Gastauer et al. 2021).

3.2.2 Collection and Preparation of Individuals

The competition between the native species *A. longispicus* and *P. cinerascens* and the invasive species *M. minutiflora* was measured in a greenhouse experiment. For this purpose, adult specimens of the native species were collected from the canga plateau N1 located in Carajás. Tillers were separated in the laboratory and cut above the first node (approximately at a height of 10 cm); dry leaves were removed.

For the invasive species, seeds were collected from a waste pile (6.05657S, 50.18059W). In the laboratory, seeds were germinated by sowing in sterilized sand and stored in a plant growth chamber (Fitotron SGC 120, Weiss Technik, Loughborough, U.K.) with a photoperiod of 12/12 hours. Daily germination monitoring was performed, and the seedlings were subsequently transported to a commercial organic substrate (Jiffy-7). Once all individuals reached 4 cm in height, we transferred them to pots with 0.6 dm³ to initiate the experiment.

3.2.3 Experimental Design

First, we delimited two competition treatments. In the intraspecific treatment, we compared the individual performances of native and invasive species on the substrates, whereas in the interspecific treatment, we examined the competitive interactions between invasive and native species. For the intraspecific treatment, we planted two individuals of the same species in each pot. For the interspecific treatment, we placed one individual of the native species and one of the invasive species in the same plot, allowing them to interact in a shared environment.

In each competition treatment, two distinct substrates were used: crushed canga topsoil and red mining waste. Both substrates exhibited similar soil properties (see TableS1), that is a higher percentage of sand, low pH, and low overall nutrient availability but high iron content.

Fertilization is common practice during mineland rehabilitation. To outline the influence of fertilization on the competitive outcomes of the tested species, a control treatment (no fertilizer) and two fertilization treatments were used for the red mining waste substrate following recommendations from rehabilitation practices: 50%N—macro- and micronutrients and the application of 80 mg/dm³ of nitrogen; and 100% N—macro- and micronutrients with the application of 160 mg/dm³ of nitrogen. The amount of additional nutrients applied did not vary among the fertilized treatments, which consisted of 200 mg P dm³ (Na₂PO₄H₂O), 200 mg Ca/dm³ (CaSO₄*2H₂O), 150 mg K dm³ (KCl), 50 mg Mg dm³ (MgSO₄*7H₂O), 4 mg Mn dm³ (MnSO₄), and 4 mg Zn dm³ (ZnSO₄*7H₂O), and 1.5 mg Cu dm³ (CuSO₄*7H₂O). Prior to the installation of the experiment, the nutrients were weighted individually for each pot, considering a pot volume of 0.6 dm³. Nitrogen and potassium fertilization were divided into three applications, which were carried out at regular intervals of 30 days for each dose.

Finally, the experimental design included a total of 160 pots of 0.6 dm³, five biotic treatments (three intraspecific and two interspecific) × four abiotic treatments (canga, mining waste with no fertilizer and two fertilization treatments) × eight replicates. Throughout the experiment, light availability was homogeneous in the greenhouse and the individuals were spaced at a sufficient distance to prevent initial shading effects. Temperature and relative humidity were monitored with a thermos couple connected to a datalogger (RHT10, Extech Instruments). The temperature varied between 22 and 36°C, while the relative humidity had an average of 75%. Daily irrigation with distilled water was performed manually to compensate for water loss through evapotranspiration.

3.2.4 Plant Measurements

After 180 days, we counted the number of tillers for each individual and measured the above- and belowground biomass, specific leaf area (SLA), δ¹⁵N, leaf nitrogen concentration (N%), photosynthetic rate (A), stomatal conductance (gs), and transpiration for each species from each pot. A, gs, and transpiration were measured between 8:00 and 10:00 hours to avoid extreme values of air vapor pressure deficit. The newest, fully expanded leaves were selected for measurements. Measurements were performed in the central strip of the leaves using a gas exchange chamber (LI-6400XTR, LICOR, Lincoln, Nebraska, U.S.A.).

The SLA was obtained through the ratio of leaf area to dry leaf weight. The ratio between photosynthesis and transpiration was used to calculate the water use efficiency (WUE).

The shoot and root biomasses were harvested separately, washed, and oven-dried at 62°C to a constant weight. To determine the N% and $\delta^{15}\text{N}$, 1–2 mg subsamples of homogenized plant material leaves were sealed in a tin capsule. The nitrogen concentrations and isotope ratios were measured by using dry combustion in a Finnigan Delta Plus isotope ratio mass spectrometer (IRMS Delta Plus, Finnigan MAT, Germany) coupled with an elemental analyzer (CHN-1110) at the Laboratory Isotope Tracer Technologies, Inc. (Waterloo, Ontario, Canada). The nitrogen concentration was expressed as a percentage (%) with an analytical error of 0.3%. For the isotope ratio, we used delta notation ($\delta^{15}\text{N}$) on a parts-per-thousand basis (‰); the analytical error for each ratio did not surpass 0.3‰, and we used atmospheric air as the standard for $\delta^{15}\text{N}$.

3.2.5 Data Analyses

To verify the individual species performance, we performed two-way analysis of variance (ANOVA) followed by Tukey's post hoc test separately for the intraspecific and interspecific treatments, considering the response variables as shoot biomass, root biomass, number of tillers, N%, $\delta^{15}\text{N}$, SLA, and WUE, and species and substrate type (+fertilization) as predictors (canga topsoil, nonfertilized mining waste, mining waste with fertilization and 80 mg of N, and 100% N is mining waste with fertilization and 160 mg of N).

To observe how resource use efficiency and growth of native and invasive species respond to competition types, we performed two-way ANOVA followed by the Tukey post hoc test for each substrate (canga, nonfertilized mining waste, 50% N mining waste, and 100% N mining waste). Here, we considered species and competition type as predictor variables while utilizing shoot biomass, root biomass, N%, $\delta^{15}\text{N}$, SLA, and WUE as our response variables. To meet the assumption of normality, the data were log-transformed when necessary.

We also performed a principal component analysis (PCA) to verify the functional similarity of the individuals of *M. minutiflora*, *P. cinerascens*, and *A. longispicus* on different substrates under intra- and interspecific competition and the possible overlap among them using the functional traits SLA, $\delta^{15}\text{N}$, A, gs, WUE, and N%. We used K-means clustering with Euclidean distances on the first three principal components of PCA to group the genes into five functional groups. All the statistical analyses were performed using the RStudio program (R Team Core 2022).

3.3 Results

Compared to those in non-fertilized canga and mining waste substrates, the shoot and root biomasses of invasive grass increased significantly in the case of mining waste with nitrogen application (Fig.1). A similar pattern was found for shoot biomass in *Paspalum cinerascens*, while *Axonopus longispicus* showed no variation in biomass production throughout the treatments. The biomass of *Melinis minutiflora* did not differ from that of *P. cinerascens* on any of the mining waste substrates, but the root biomass was lower than that of the native species on the canga substrate. The shoot biomass of the invasive species exceeded that of *A. longispicus* in all the mining waste treatments, and no difference was found for the canga substrate.

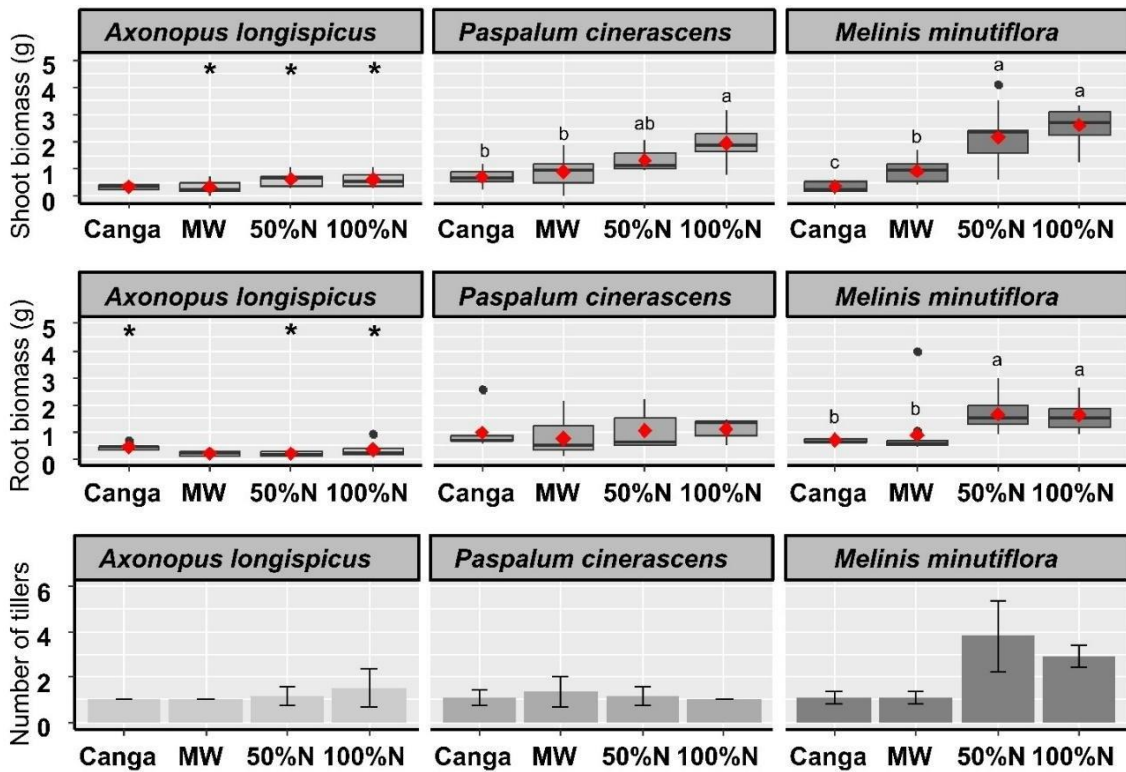


Figure 1. Figure 1 Biomass and tillering of the native and invasive grass species under intraspecific conditions from different substrates and fertilization treatments (canga, canga topsoil; MW, mining waste, 50% N—mining waste with fertilization and 80 mg of N, and 100% N—mining waste with fertilization and 160 mg of N). Different letters indicate significant differences between substrates within species ($p < 0.05$), and “*” indicates differences ($p < 0.05$) between native and invasive species according to post hoc Tukey’s test. The bar height is the mean number of tillers, and the error bars represent \pm SD.

Nitrogen application increased foliar nitrogen in all species, which was greatest in *A. longispicus*, followed by *P. cinerascens* (Fig.3). *A. longispicus* had the lowest $\delta^{15}\text{N}$ values, but there were no differences among the treatments, while fertilization reduced the high $\delta^{15}\text{N}$ found

in *M. minutiflora* plants grown in canga or unfertilized mining waste. *M. minutiflora* had a greater SLA than did the native species. No differences were found among treatments regarding WUE, photosynthetic rate, or stomatal conductance, but native species had greater stomatal conductance than *M. minutiflora*.

When cultivated in competition with *M. minutiflora*, the shoot biomass of both native species did not differ significantly between treatments (Fig.2; however, the detailed results are provided in Table S2). With fertilization, *M. minutiflora* was able to increase its biomass, while that of the native species decreased in response to intraspecific competition. In the 50% nitrogen treatment, the biomass of the invasive species was up to seven times greater than that of *P. cinerascens* and nine times greater than that of *A. longispicus*.

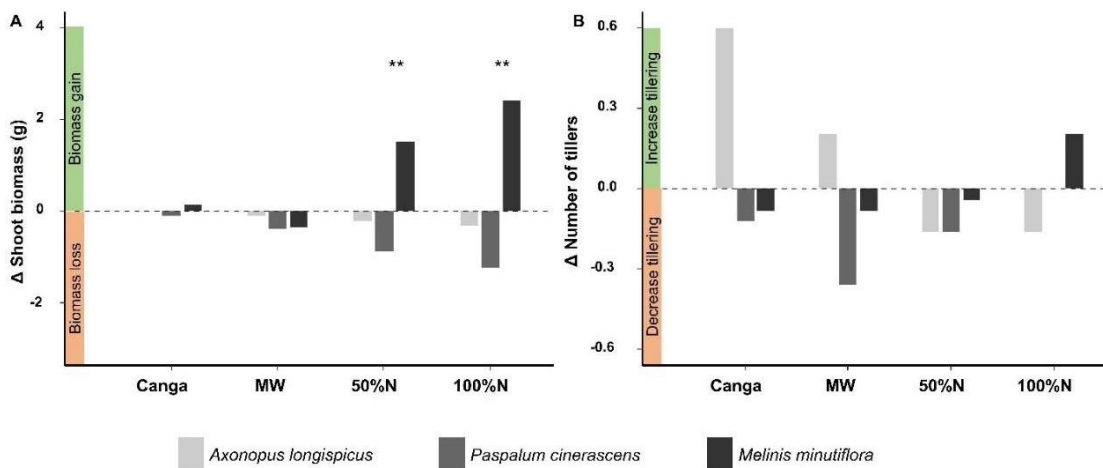


Figure 2 A) Mean difference in shoot biomass (g) of native and invasive species under interspecific competition compared to intraspecific treatments. The symbol “**” indicates a significant difference in shoot biomass between native and invasive species (pvalue <0.05) compared to the intraspecific treatments. (B) Mean difference in the number of tillers of native and invasive species under interspecific competition compared to intraspecific treatments (canga is canga topsoil, MW is nonfertilized mining waste, 50% N is mining waste with fertilization and 80 mg of N, and 100% N is mining waste with fertilization and 160 mg of N).

Regarding leaf traits, most of the trends observed under intra-specific conditions, that is an increase in foliar nitrogen accompanied by a reduction in $\delta^{15}\text{N}$ with fertilization and a greater SLA in invasive than in native species and no clear pattern for photosynthetic rate and stomatal conductance, were maintained when the plants were grown under interspecific conditions (see Table S3; Fig.3). Furthermore, most leaf traits of the examined species did not differ between intra- and interspecific conditions, but some important tendencies are noteworthy. First, there was reduced foliar nitrogen under interspecific conditions, principally in native

species. Second, the $\delta^{15}\text{N}$ values tended to be lower than those in the intraspecific treatments, except for *A. longispicus*. Third, the SLA of native species was lower than that under interspecific conditions, especially when cultivated in fertilized treatments. Fourth, compared to that under intraspecific conditions, the stomatal conductance of both native species tended to decline in the interspecific treatments, while that of the invasive species increased.

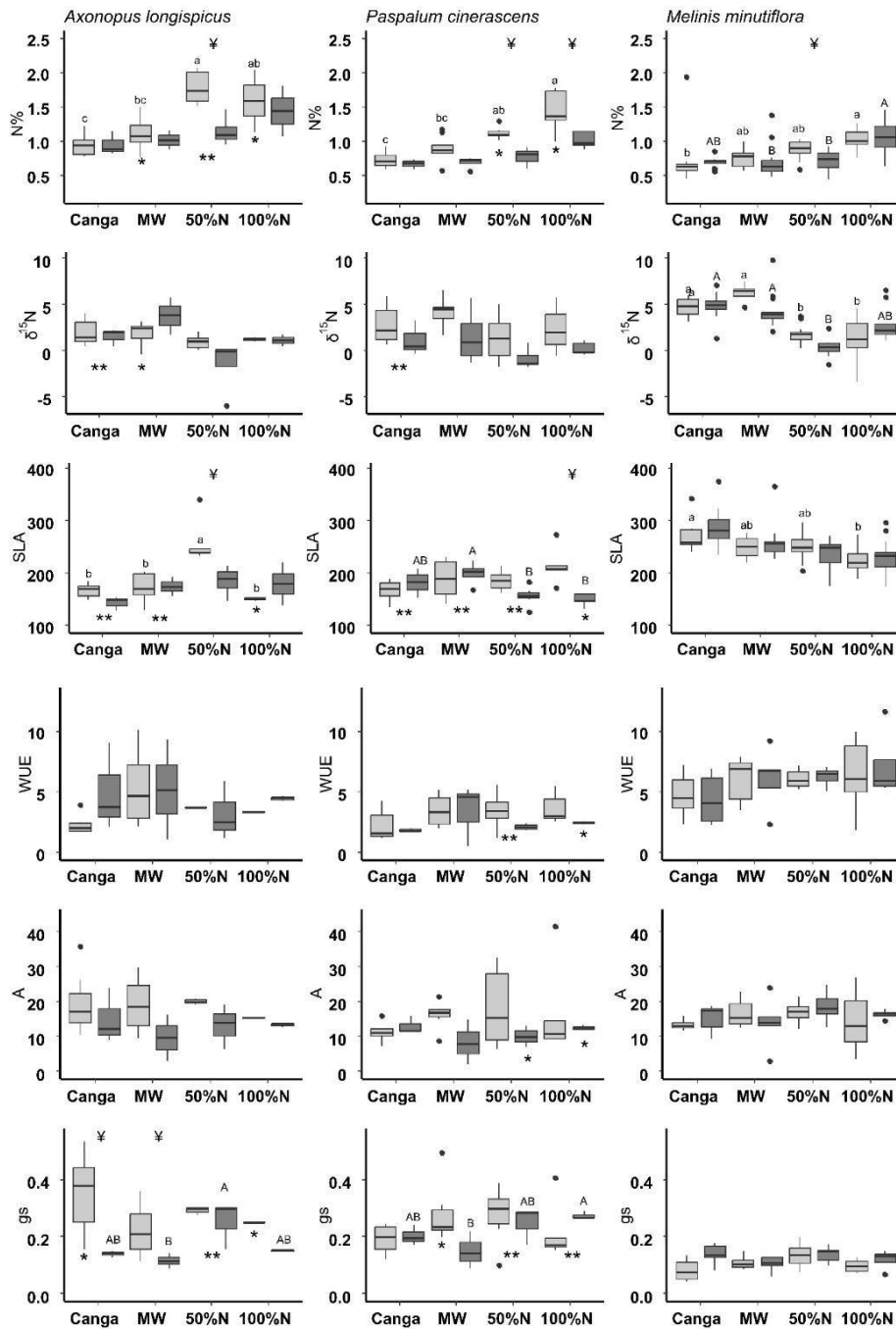


Figure 3 Leaf nitrogen content (N%), stable N isotope ratio ($\delta^{15}\text{N}$), specific leaf area (SLA), water use efficiency (WUE), photosynthetic rate (A), and stomatal conductance (gs) between native and invasive species under intra- (light gray) and interspecific (dark gray) competition on different substrates (canga, cangatopsoil; MW, mining waste; 50% N—mining fertilization with 80 mg of N; and 100% N—mining waste with 160 mg of N). Lowercase

letters indicatedifferences between substrates for each species under intraspecific competition, uppercase letters indicate differences between substrates for each species underinterspecific competition, Asterisks indicate a significant difference between native and invasive species on the same substrate (*'is significance level of 0.05, '**'is significance level of 0.01), and'Ψ'indicates the difference between intra- and interspecific competition.

The first three principal components (PCs) explained 75% of the leaf functional space of the three species analyzed here (Fig.4; for variable loadings and eigenvalues of the PCs, please see Tables S4 & S5). The invasive species occupied the region of the functional space associated with acquisitive traits (i.e. higher values of SLA and WUE), while the native species occupied the region associated with nitrogen content and stomatal conductance. PC1 separated invasive and native species according to SLA, WUE, and gs. In general, individuals of *M. minutiflora* in the fertilized treatment had negative values of PC2 related to photosynthesis and resource availability (higher leaf nitrogen and photosynthetic rate), while individuals in the mining waste and canga substrate treatments had higher $\delta^{15}\text{N}$ values. The native species exhibited a different pattern; here, interspecific competition caused leaf trait displacement, whereas intraspecific competition had a positive effect on N% and photosynthetic rate (Fig.4). K-means cluster analysis based on the first three components divided the individuals into five groups (Figs.S2 & S3).

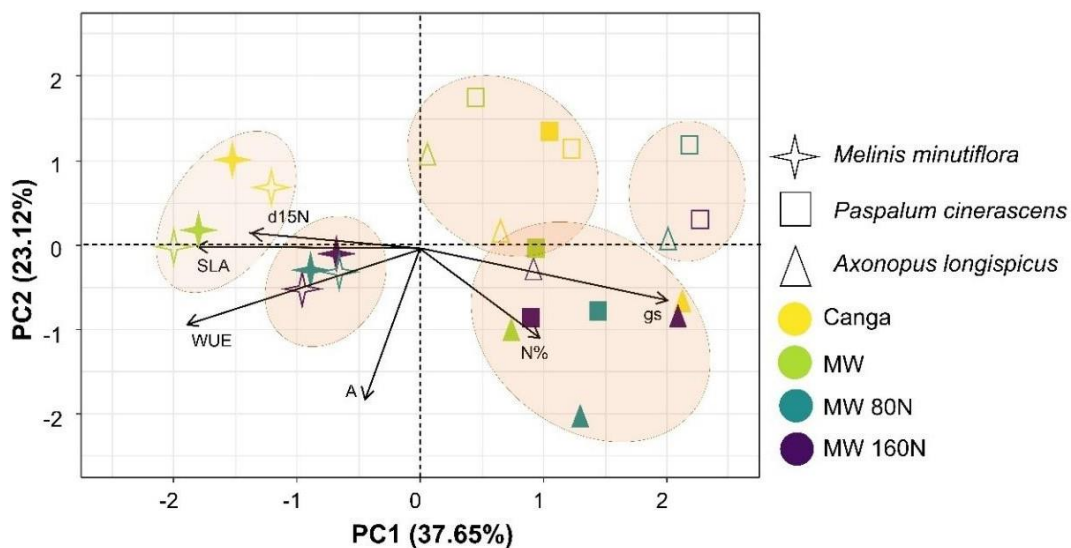


Figure 4 Figure 4. Functional space (from the functional traits SLA, $\delta^{15}\text{N}$, A, gs, WUE, and N%) of the invasive *Melinis minutiflora* and native *Paspalum cinerascens* and *Axonopus longispicus* in intra- (filled symbols) and interspecific (unfilled symbols) competition as a function of substrates and fertilization. The symbols represent the centroid of each species group in the substrates. The ellipses represent clusters formed by the K-means test. Canga is canga topsoil, MW is nonfertilized mining waste, 50% N is mining waste with fertilization and 80 mg of N, and 100% N is mining waste with fertilization and 160 mg of N).

3.4 Discussion

The species growth, resource use strategies, and competitive outcomes between native and invasive species were influenced by nutrient application. In summary, all the species included in this study developed in all the treatments (at the substrate and fertilization levels), indicating that substrate specificity, such as dystrophic canga topsoil (Skirycz et al.2014), does not preclude any of the species tested here. Nutrient application increases the biomass of *Paspalum cinerascens* and invasive (*Melinis minutiflora*) species when they are not grown in inter-specific competition. Furthermore, our results showed that inter-specific fertilization favors molasses grass, confirming the high competitiveness of *M. minutiflora* with increases in nitrogen availability (Eller & Oliveira2017). These findings have two important implications for practice. First, population control of invasive molasses grass in rehabilitating minelands from the Carajás National Forest is necessary to reduce propagule pressure in native ecosystems, as canga soils do not filter out invasive species. Second, the avoidance of fertilization decreases the growth performance of invasive species and strengthens the coexistence of native canga grasses, facilitating population control of molasses grass.

Fertilization resulted in higher leaf nitrogen in both native species when the plants were grown under intraspecific conditions, although the greater leaf nitrogen in *Axonopus longispicus* did not increase its growth performance (in this study, but see Caldeira et al. 2021). However, functional responses change due to interspecific competition, and we observed alterations in leaf eco-nomic traits, indicating that the development of native species was affected by the presence of *M. minutiflora* (Violle et al. 2009; Liu et al.2019). Decreases in SLA and stomatal conductance usually suggest low nutrient availability (Freschet et al.2015) as a result of competition, causing lower biomass production in native species, when competing with molasses grass. When grown together, the N% in native species decreases to the level of that in unfertilized plants, whereas that in invasive plants maintains leaf nitrogen concentrations and increases growth performance. This acquisitive strategy confers a competitive advantage on *M. minutiflora* over native species characterized by rapid nutrient acquisition, growth, and reproduction, as observed for other invasive species (Eller &Oliveira 2017; Liu et al. 2019; Mathakutha et al. 2019; Fernandes et al. 2021; Montesinos 2021). Thus, even though native species respond positively to fertilization when grown in isolation, competition with molasses grass leads to a preemption of nutrients, reducing resource availability for the native species (Craine & Dybzinski 2013).

The absence of fertilization can thus offer a viable option to mitigate the invasibility of *M. minutiflora* during the rehabilitation process (Baer et al. 2004). Although *M. minutiflora* can endure such conditions, its reduced growth performance in these substrates indicates that it may not succeed in terms of territorial dominance. We observed that the functional traits of invasive species were not influenced by competition, and phenotypic variation was observed between nonfertilized and fertilized substrates. The similarity in functional response between these environments, also observed in biomass production, indicates tolerance of different nitrogen supplies of *M. minutiflora* but lower invasiveness in areas with lower nutritional availability, such as canga. Interestingly, nitrogen dynamics are reportedly affected by *M. minutiflora*, especially during a more open cycle (Yelenik & D'Antonio 2013; Ribeiro et al. 2017; Sena-Souza et al. 2023). This is because *M. minutiflora* can increase nitrate availability in the soil by potentializing the nitrifying microbial community. This increases the nitrogen supply in the soil and, consequently, the foliar $\delta^{15}\text{N}$ of invasive species (Ribeiro et al. 2017; Zhang et al. 2022). Furthermore, invasive species were able to maintain higher WUE and increase nitrogen use efficiency. Several additional factors, such as propagule pressure, disturbance, and water limitation, need to be addressed because they may influence the invasion of *M. minutiflora* and change the outcomes observed here (Rojas-Botero et al. 2021). Nevertheless, these findings reveal the behavior of invasive species in limited environments.

The functional response of both native species did not differ between unfertilized mining waste and canga topsoil. Plants that have adapted to soils with low nutrient availability exhibit resource traits characterized by conservative use resulting from adaptive fitness responses (Silveira et al. 2015). For instance, native species tend to invest more in leaf thickness and produce rich nitrogen leaves and lower $\delta^{15}\text{N}$ than invasive species. *A. longispicus* appears to rely on a distinct nitrogen source from invasive species in unfertilized treatments, which may be attributed to symbiosis with nitrogen-fixating bacteria, as observed in other *Axonopus* species (Marques et al. 2017). The exploitation of different nitrogen sources may explain the homogeneity of biomass production observed for this species across fertilization treatments. Further studies should assess sources of resources such as water and nitrogen to understand the species' ability to overcome resource restrictions (Boanares et al. 2019; Gachara et al. 2023); as such, an interaction would additionally qualify this species for mineland rehabilitation activities.

In contrast, competition with *M. minutiflora* grass did not change the functional trait responses of native species in unfertilized treatments. This finding suggested that in

environments with low resource availability, *P. cinerascens* was able to maintain normal biomass production and that competition with invasive grass did not influence species performance. Such adaptations could account for the ability of this species to thrive in limiting environments, which not only position native species favorably in resource-scarce ecosystems such as cangas (Silveira et al. 2015) but also present an opportunity to reconsider conventional rehabilitation practices that rely heavily on nitrogen-based fertilization (Funk et al. 2013). Furthermore, studies focusing on the performance of additional native species from canga ecosystems in competition with invasive grasses are necessary to improve species selection from plant communities in this natural environment.

Native vegetation cover is an important goal during the early stages of rehabilitation, as it also reduces and mitigates invasive species (Young et al. 2022; Castro et al. 2023); moreover, our results highlight that the use of fertilization disproportionately enhances *M. minutiflora* compared to the native grasses tested here. Overall, soil cover may be negatively impacted by the absence of fertilization, as nutrient availability at rehabilitation sites is low (Silva et al. 2018). However, native species from canga ecosystems are well suited to thrive under such conditions and may have lower nutrient requirements (Skiryicz et al. 2014). Simultaneously, attaining peak native yield and minimizing invasive growth were achievable in nonfertilized treatments, thereby optimizing environmental quality and mitigating risks for neighboring areas such as cangas or further rehabilitating sites by reducing propagule pressure. Furthermore, the lack of fertilization within rehabilitated sites can facilitate manual or chemical eradication, enabling more effective progression of the rehabilitation process in the long term. This strategy is particularly crucial for mitigating the operational risks and costs associated with combatting and eradicating invasive species in minelands while safeguarding the integrity of neighboring sites until the ability of additional species to outcompete molasses grass is tested.

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3.6 Supporting Information

The following information may be found in the online version of this article:

Table S1. Soil chemical conditions of the substrates used in the experiment.

Table S2. Shoot and root biomass of the native and invasive species under interspecific competition treatments (mean SE).

Table S3. Leaf nitrogen content (N%), $\delta^{15}\text{N}$, specific leaf area (SLA), water use efficiency (WUE), photosynthetic rate (A), and stomatal conductance (gs).

Table S4. Variable correlations with principal component analysis (PCA) components for functional traits across substrates and fertilization levels.

Table S5. Eigenvalues, variance explained %, and cumulative proportion of total variance from principal component analysis (PCA) components for functional traits across substrates and fertilization levels.

Figure S1. Location of Serra dos Carajás, PA-Brazil (red dot) highlighting known occurrences of the invasive species *Melinis minutiflora*.

Figure S2. Optimal K-means clusters by the elbow method.

Figure S3. Illustration of the clusters generated by K-means (SS=82.2%)

4. SESSÃO II

Functional homogenization by the invasive species *Muntingia calabura* L. and its management implications for mineland rehabilitation in tropical region

A segunda sessão desta tese será submetida na revista Restoration Ecology. A sessão foi elaborada e formatada conforme as normas da publicação científica disponível em:

<https://onlinelibrary.wiley.com/doi/epdf/10.1111/rec.14108>

Functional homogenization by the invasive species *Muntingia calabura* L. and its management implications for mineland rehabilitation in tropical region

ABSTRACT

Invasive plant species are a major threat to biodiversity and represent one of the main challenges to ecological restoration, as they can limit the establishment of native species and alter both taxonomic and functional diversity. A functional trait-based approach is essential to understand invasion mechanisms, evaluate impacts on ecosystem functioning, and support management strategies in restoration contexts that are highly susceptible to reinvasion. This study aims to assess the taxonomic and functional impacts of the invasive species *Muntingia calabura* on native plant communities in rehabilitated sites, with implications for the management and restoration of tropical ecosystems. Vegetation and soil data were obtained from long-term monitoring plots established in rehabilitated mining areas of the Carajás National Forest, classified as invaded or non-invaded by *M. calabura*. Differences between invaded and non-invaded communities were evaluated by comparing patterns of species composition and functional structure, and by examining how the invasive species is positioned within the functional space of native communities. In addition, we assessed how soil properties and the abundance of the invasive species influence the functional characteristics of native plant communities. Our results show that invasion by *M. calabura* reshapes the functional structure of native woody communities mainly by altering species dominance and trait weighting, rather than causing strong native species loss. Although ecosystem functioning appeared to be maintained, invaded sites exhibited reduced functional richness and increased functional homogenization, potentially limiting community resilience. Functional similarity between the invasive and native species facilitated invasion under strong environmental filtering but did not prevent substantial functional restructuring. These findings highlight the need for restoration strategies that go beyond invasive species control and explicitly promote functional diversity, redundancy, and the reintroduction of key native functional species to enhance long-term ecosystem recovery.

Key words: *canga* ecosystems, Carajás National Forest, interspecific competition, invasion management, *Melinis minutiflora*, resource use

Implications for Practice

- Rehabilitation efforts should move beyond invasive species removal and actively promote native species that contribute most to functional diversity, including dominant and functionally original species.
- Selecting native species with complementary functional traits and higher redundancy can increase resistance to reinvasion and enhance ecosystem resilience in post-mining landscapes.
- Restoration planning should explicitly consider soil conditions and environmental filtering to guide species selection and management actions that support long-term functional recovery.

4.1 Introduction

Invasive plant species represent a major threat to biodiversity and are recognized as one of the main barriers to successful ecological restoration (D'Antonio et al. 2016; Vantarová et al. 2023). After establishing and spreading, these alien species can hinder the establishment of native plants, thereby affecting both the taxonomic and functional diversity of native communities in restoration sites (Blackburn et al. 2011; Tordoni et al. 2019). Understanding the impacts and interactions between native and invasive species is thus crucial for developing effective strategies to combat biological invasions. This is especially relevant because the simple removal of invasive species is often insufficient in the long term (Weidlich et al. 2020), particularly in restoration sites, where community assembly is still in progress and thus remain highly susceptible to reinvasion.

A functional perspective provides a robust framework for understanding how species influence ecosystem functioning through their ecological traits. By linking traits to ecological processes, this approach allows the assessment of invasion impacts on native communities and supports management decisions (Funk et al., 2016; Huxley et al., 2023; Mathakutha et al., 2019; Gioria et al., 2023). In invaded systems, the dominance of invasive species commonly may lead to reduced functional diversity and increased functional homogenization in native communities (Bando et al. 2023; Larsen et al. 2023). These changes are reflected in key functional metrics, including functional richness, which captures the range of ecological strategies present, and community-weighted means (CWMs), which describe the dominant functional strategies shaped primarily by the most original trait and/or most abundant species (Garnier et al., 2004; Gaüzère et al. 2019; Petruzzella et al., 2020). Examining native species' contributions to CWMs helps identify species or functional groups that disproportionately drive ecosystem functioning and reveals how their influence is altered under invasion pressure (Guido et al., 2021), particularly given the role of dominant species in conferring resistance to biological invasions (Ernst et al., 2023, Wang et al. 2022). Consequently, shifts in CWMs or the contribution of species can infer the loss or weakening of key native functional roles following invasion, offering important insights about the effects of invasion on community composition and ecosystem functioning necessary to design management of restoring ecosystems.

Beyond identifying functional losses in native communities, evaluating the degree of functional similarity between invasive and native species provides additional insights about the mechanisms underlying their establishment (Funk et al., 2008). This is particularly relevant

because high functional diversity is expected to enhance community resistance to invasion (Maron & Marler, 2007), especially when niche differentiation limits the success of functionally redundant invaders. In this context, the limiting similarity hypothesis predicts that resident species with similar functional traits compete more intensely for shared resources, which can prevent the establishment of invaders whose traits strongly overlap with those of native species (MacArthur & Levins 1967; Yanneli et al. 2017). In contrast, habitat filtering occurs when environmental conditions favor species with similar trait combinations, allowing species with similar functional traits to persist under the same environmental constraints and potentially leading to functional convergence between native and invasive species, as described by the join-the-locals hypothesis (Pearson et al., 2018; Tecco et al. 2010; Yi et al., 2025). Integrating measures of functional diversity and functional similarity therefore enables the evaluation of invasion mechanisms and their ecological consequences, while helping identify native species that may compensate for lost functions and informing rehabilitation strategies aimed at enhancing ecosystem resilience.

These functional patterns are particularly relevant in tropical rehabilitation areas, where biological invasions can jeopardize ongoing rehabilitation efforts. Several invasive plant species have been reported in several conservation units, including the Carajás National Forest in Southeastern Amazon, Pará, Brazil (ICMBio, 2025; Giuliatti et al., 2018), an area characterized by high levels of species diversity and endemism. This conservation unit forms part of a mosaic of protected areas within the arc of deforestation of the Amazon biome and is subject to mining activities, for which ecological rehabilitation is legally required to restore ecosystem functions and services (Gastauer et al. 2018). During the rehabilitation process, invasive species such as *Muntingia calabura* L. (Muntingiaceae) have emerged as a major management concern, underscoring the need for effective control strategies (ICMBio 2025). Understanding the ecological mechanisms underlying successful invasions can improve our ability to manage invasive populations and support the design of more effective rehabilitation strategies, including the selection of suitable native species, enrichment plantings, and appropriate soil conditioning practices (Boanares et al., 2023; Castro et al., 2024; Massante et al., 2023).

The aim of this work is to assess the taxonomic and functional effects of the invasive species *M. calabura* in the remaining native communities in rehabilitated sites, providing insights for management and restoration strategies. Specifically, we asked: (1) do species and

(2) functional richness and composition of native communities change with invasion in rehabilitated sites?; (3) do invaded areas differ from non-invaded areas in the structuring of native species contributions to community-weighted mean functional traits, and is this difference associated with the functional similarity between the invasive species and native species?; and (4) does variation in soil properties and invasive species abundance influence the distribution of functional traits of native plant communities in rehabilitated sites?

4.2 Methods

4.2.1 Study Site

This study was carried out in the rehabilitation sites in Carajás National Forest, a category IV conservation unit (protected area managed for habitat and species conservation through active management) of approximately 4,120 km² in eastern Amazon, Brazil. The region is characterized by a tropical seasonal climate, Aw in the Koeppen classification, with a total precipitation of approximately 2,000mm and daily mean temperatures above 24°C throughout the year (Alvares et al. 2013). Precipitation is concentrated between October and April, and monthly rain does not surpass 60 mm in the dry season from May to September.

Semi-deciduous, evergreen dense or open sub-montane forests dominate the vegetation of the conservation unit, but patches of canga vegetation, i.e., ferruginous savanna formations characterized by rare and endangered diversity (Giulietti et al. 2019), can be found above ironstone outcrops on mountaintops (Viana et al. 2016). Furthermore, the landscape is characterized by open-cast iron ore mines and waste piles, i.e., areas where inert overburden material from the extraction process is deposited. These slopes are hydroseeded with a mixture of soil amendments, including fertilizers and organic matter, to promote vegetation establishment and support the recovery of forest ecosystem characteristics. The seed mixtures currently used consist mainly of non-invasive commercial fast-growing legumes and grasses intended to trigger the rehabilitation process (Silva et al., 2018; Gastauer et al., 2022). To improve the environmental performance of rehabilitating areas, additional native species from both forest and canga ecosystems have been studied for incorporation into rehabilitation programs (Gastauer et al., 2020).

Invasive species have been recorded in natural, disturbed, and rehabilitating environments within the Carajás National Forest (Augusto et al., 2016; ICMBio 2025; Giulietti et al., 2018). Among them, *Muntingia calabura* L. (Muntingiaceae), is native to tropical

America. This species produces flowers and fruits throughout the year, and self-pollination has been documented, allowing it to set seeds and persist in degraded sites even in the absence of pollinators (Figueiredo et al., 2008). To comply with environmental regulations and improve rehabilitation outcomes, the management of this species involves manual cutting and, when necessary, the selective application of chemical weeding.

4.2.2 Data collection

We used a vegetation and soil database derived from long-term monitoring of 54 permanent plots established in forest formations undergoing rehabilitation (3–8 years since rehabilitation), originally designed to report annual rehabilitation progress to environmental licensing agencies (Gastauer et al. 2021). Vegetation and soil were sampled in permanent plots of 10 × 20 m, spaced at least 50 m apart. Of the 54 plots available in the monitoring database, 47 contained arboreal–shrub vegetation and were included in the analysis. These plots were classified as invaded (16 plots) or non-invaded (31 plots) based on the presence of the invasive species *Muntingia calabura*. The unpaired sampling design reflects the spatial distribution of the invasive species across rehabilitation areas and the monitoring-based nature of the dataset. Within each plot, all trees with a diameter at breast height (DBH) greater than 3 cm were tagged, identified to species level, and included in the analyses. Composite soil samples were obtained from five sampling points per plot at a depth of 0–10 cm. Additionally, we used the species list and trait database compiled from preserved areas of the region, including canga ecosystems (Gastauer et al. 2020) and adjacent evergreen dense forests (Gastauer et al. 2021), to characterize the functional traits of native tree species from the region.

For this study, we selected leaf traits related to competition, resource use and acquisition strategies, as well as reproductive and dispersal traits linked to the ability of species to colonize new areas. In total, we used nine functional traits (height, DBH, specific leaf area - SLA, leaf $\delta^{13}\text{C}$, leaf $\delta^{15}\text{N}$, foliar phosphorus content, and leaf C:N ratio) and two categoric traits (pollination and dispersal syndromes), according to table 1.

Table 1 Functional traits analyzed and their ecophysiological implications related to resource-use strategies, competition, reproduction, and dispersal in rehabilitating forest formations.

Trait	Type	Ecophysiological implication
Height	Quantitative	Proxy for competitive ability for light

Trait	Type	Ecophysiological implication
		acquisition and vertical stratification. (Díaz et al. 2016)
DBH	Quantitative	Indicator of plant size, biomass accumulation, and carbon storage capacity. (Díaz et al. 2016)
Specific leaf area (SLA)	Quantitative	Reflects resource-use strategy; high SLA is associated with fast growth and acquisitive strategies, while low SLA indicates conservative resource use. (Wright et al. 2004)
leaf $\delta^{13}\text{C}$	Quantitative	Proxy for intrinsic water-use efficiency and carbon assimilation strategy. (Farquhar et al. 1989)
leaf $\delta^{15}\text{N}$	Quantitative	Indicates nitrogen sources and cycling processes; may reflect nutrient availability and plant–soil interactions. (Vitousek et al. 2013)
foliar phosphorus content	Quantitative	Reflects nutrient acquisition capacity and potential photosynthetic performance. (Wright et al. 2004)
leaf C:N ratio	Quantitative	Indicates nutrient-use strategy and leaf tissue quality; high values are associated with conservative strategies and slower decomposition rates. (Díaz et al. 2016; Wright et al. 2004)
Pollination syndromes	Categorical	Relates to reproductive strategy and dependence on specific pollinator groups.
Dispersal syndromes	Categorical	Indicates colonization potential and spatial dispersal capacity. (Mayfield, Ackerly, Daily, 2006)

For trait collection, we measured at least one individual per species per plot, ensuring a minimum of three individuals per species. DBH was measured using a measuring tape, and tree

height was visually estimated. To determine SLA, five sun-exposed, fully expanded, and healthy leaves (without signs of herbivory or pathogens) were collected from each of the selected individuals. Fresh leaves were scanned to measure leaf area using ImageJ software, oven-dried at 60 °C until constant weight, and then weighted. SLA was calculated as the ratio between fresh leaf area and dry leaf mass.

Additionally, ten leaves from each of the three individuals per species were collected for the determination of nitrogen (N), carbon (C), and phosphorus (P) concentrations, as well as for stable isotope analyses of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$). To determine the N and C concentration and $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$, 1–2 mg subsamples of homogenized plant material leaves were sealed in a tin capsule. The nitrogen and carbon concentrations and isotope ratios were measured by using dry combustion in a Finnigan Delta Plus isotope ratio mass spectrometer (IRMSDelta Plus, Finnigan MAT, Germany) coupled with an elemental analyzer (CHN-1110) at the Laboratory Isotope Tracer Technologies, Inc. (Waterloo, Ontario, Canada). The CN ration was then defined as the relation between carbon and nitrogen content. The rest of the plant material were then sent to the Brazilian Laboratory of Environmental and Agricultural Analyses (LABRAS – Monte Carmelo, Minas Gerais) and the phosphorus were determined after sulfuric acid digestion with the analytical detection limits of 0.3 g kg⁻¹. Dispersion and pollination syndromes were gathered through a bibliographic survey; and when the syndromes were not available for the species, we used the dominating genus information.

Soil samples were air-dried and sieved to 2 mm. The pH was determined in a soil: liquid suspension, with H₂O and CaCl₂ (1:2.5 v/v). Available P, K, Na, Fe, Cu, Mn, and Zn were determined by the Mehlich-1 extractor (Mehlich 1953), and potential acidity (H⁺Al) was determined using SMP buffer solution extractor (Shoemaker et al. 1961; van Raij et al. 2001). Soil texture (Clay, Silt and Sand) was determined by the hydrometer method (Bouyoucos 1962), using 50 g of soil dispersed in NaOH solution.

4.2.3 Data Analysis

All analyses were carried out in the R environment (R Core Team, 2025). To examine differences in taxonomic and functional composition, we applied Non-metric Multidimensional Scaling (NMDS) (Oksanen et al. 2025). Taxonomic differences were derived from Bray–Curtis dissimilarity. To address whether invasions influence functionality of the plant communities, we quantified functional diversity as FRic, and compared dominant community functioning

using community-weighted means (CWM) of functional traits (DBH, height, SLA, foliar P, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, and C:N ratio) (Laliberté & Legendre, 2010; Villéger et al. 2008). Differences between CWM values among invaded and non-invaded sites were tested with Wilcoxon tests. Furthermore, we used NMDS ordination based on Gower distances between plots' of CWM values to check for differences in the functional space occupied by invaded and noninvaded communities. Significance was evaluated using PERMANOVA (adonis) with 999 permutations.

We calculated the species-specific contribution to the community weighted mean (CWM) (Gaüzère et al. 2019). For that, species-specific originality (O_i) was initially calculated as the difference between the trait value (t_i) of species i and the plot-level CWM:

$$O_i = t_i - CWM$$

To quantify the strength of species contributions independently of direction, we used the absolute value of originality. Species contribution (C) was then estimated as the product of relative abundance and absolute originality, such that higher values indicate species that most strongly influence the functional structure of the community, regardless of whether their trait values are above or below the CWM

$$C_i = \frac{n_i}{\sum_{j=1}^S n_j} * |O_i|$$

where n_i is the abundance of species i and S is the total number of species in the plot.

To determine the functional position of the invasive species within the native communities, a Principal Coordinates Analysis (PCoA) was conducted using the Gower distance of functional traits DBH, height, SLA, foliar P, $\delta^{15}\text{N}$, $\delta^{13}\text{C}$, C:N ratio and two categoric traits pollination and dispersal syndromes with the 'cmdscale' function. The first three PCoA axes were used to construct a convex hull representing the functional space of species present in the restoration sites, and the invasive species was projected onto this space to assess its functional position relative to native species. We additionally incorporated species from nearby protected areas to identify new candidates for restoration management. To identify the native species functionally most similar to the invader, we calculated pairwise functional distances between the invasive species and the native species pool, considering the final species list from both rehabilitation sites and nearby protected areas.

Redundancy analysis (RDA) was performed to evaluate the relation between soil properties and invader abundance to functional aspects of native communities in invaded and non-invaded areas. A total of 23 soil chemical and physical variables were initially considered: pH, P, Na, K, S, Ca, Mg, Al, H+Al, OM, OC, total N, B, Fe, Mn, Zn, SB, V, m, clay, silt, and total sand, in addition to invader abundance. Prior to analysis, variables were tested for normality, log-transformed when necessary, standardized, and filtered to remove highly correlated predictors ($|r| \geq 0.7$). These explanatory variables were related to native community functional metrics, FRic, and CWM values of $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C:N ratio, foliar P, SLA, height, and DBH. The significance of the RDA model and individual predictors was assessed using permutation tests (1000 permutations).

4.3 Results

We recorded a total of 249 species distributed across 51 families and 144 genera. The most species-rich family was Fabaceae, with 53 species. Among these, 164 species were detected in nearby natural areas, while 85 species occurred in the rehabilitation sites, representing 24 families and 51 genera. Within the rehabilitation sites, Fabaceae was the most representative family, comprising 30 species. Invaded rehabilitation areas contained 54 native species and one invasive species, whereas non-invaded areas harbored 74 species.

Sample-based rarefaction and extrapolation showed no significant difference in richness (Fig.1A) and no difference in taxonomic native species composition between invaded and non-invaded sites were observed (Fig.5B). Regarding functional analysis, invaded communities showed lower functional richness than non-invaded communities and functional composition was different between invaded and non-invaded sites (Figure 5C and D). Functional space of invaded communities is smaller than of non-invaded, which is consistent with lower FRic detected in invaded communities.

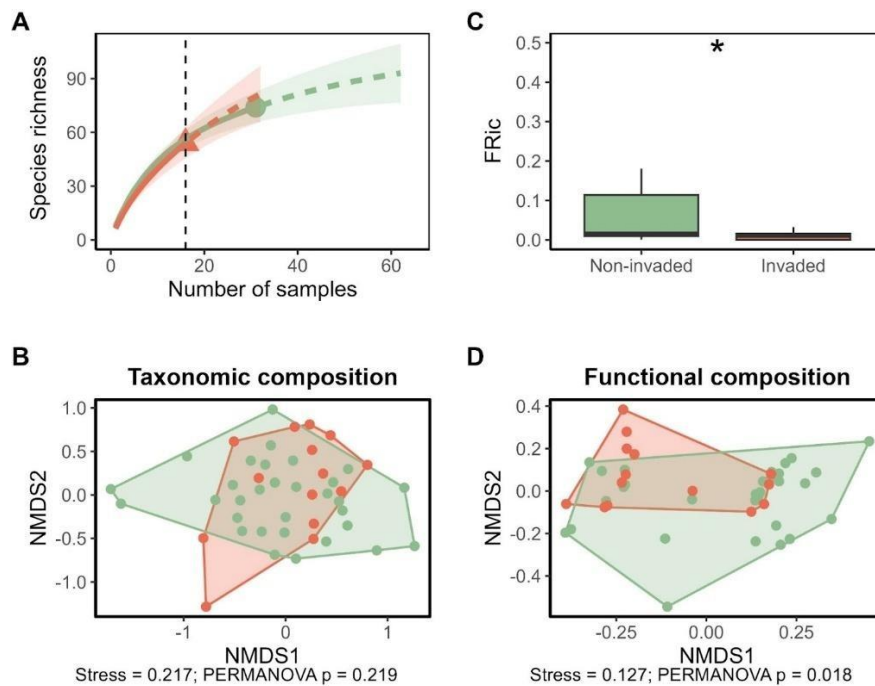


Figure 5 Taxonomic (left panels) and functional (right panels) structure of invaded (red) and non-invaded (green) rehabilitation sites. A - Sample-based rarefaction (solid lines) and extrapolation (dashed lines) curves for species richness ($q = 0$); shaded areas indicate 95% confidence intervals. B - Functional richness (FRic) of native communities in invaded and non-invaded sites, with asterisks indicating significant differences according to Wilcoxon tests ($p < 0.05$). B and D - Non-metric multidimensional scaling (NMDS) illustrates taxonomic (B) and functional (D) composition of communities. Stress values are shown for NMDS ordinations, and differences in community composition were tested using PERMANOVA.

The community-weighted means (CWM) of functional traits for native communities did not differ significantly between sites, except for leaf phosphorus content, which is lower in non-invaded communities (Figure 6).

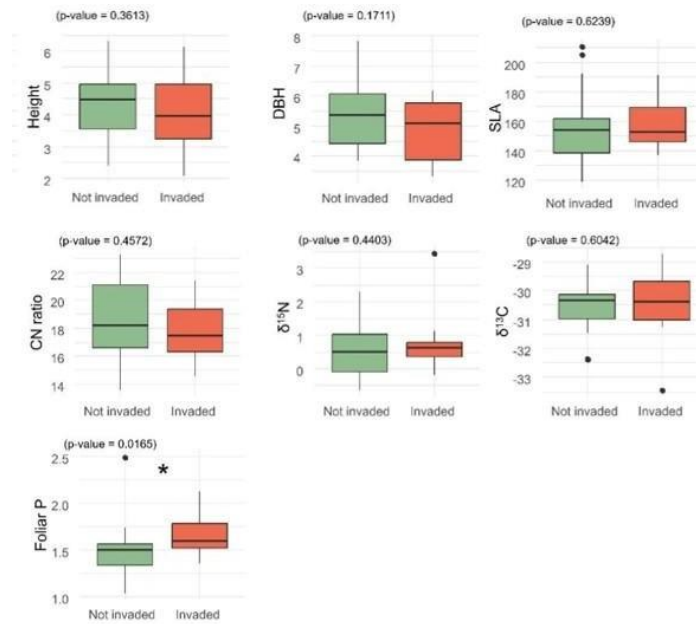


Figure 6 Community-weighted mean (CWM) trait values of native communities in invaded and non-invaded rehabilitation sites. The symbol “*” indicate significant differences according to the Wilcoxon test ($p < 0.05$).

Species contributions to community-weighted mean (CWM) values differed between invaded and non-invaded sites across multiple traits (Figure 7). In invaded sites, CWM values were driven by a smaller set of species with higher contributions, whereas in non-invaded sites contributions were more evenly distributed among species. This pattern was observed for traits related to plant size (height, DBH) and resource-use strategies (SLA, C:N ratio, foliar P, $\delta^{15}\text{N}$, and $\delta^{13}\text{C}$). A significant positive relation between species contribution to CWM and functional originality was detected for foliar P in both invasion conditions (Supplementary material – S3T2). This indicates that, regardless of invasion status, species with higher functional originality triggered community-level foliar P.

The more even distribution of contributions in non-invaded sites reflects a larger set of native species with strong influence on CWM values (Figure 6). In these sites, functionally more original species showed high contributions for specific traits, whereas in invaded sites these same species were frequently absent or exhibited near-zero contributions. Interestingly, the species *Byrsonima crispera* and *Miconia cuspidata* showed high contributions to the CWM values and were also highly functional similar to the invasive species (functional distance = 0.133, 0.049, respectively; S3T2), but reduced or null contributions under invasion. In contrast, invaded sites were characterized by a narrower subset of species dominating CWM values, with contributions concentrated in fewer taxa and reduced variability among plots. Some native

species, such as *Piper aduncum*, *Mimosa acutistipula*, and *Vismia baccifera* (functional distance = 0.113, 0.693, and 0.136, respectively), maintained similar contributions across both invaded and non-invaded conditions, indicating persistence of a limited set of functional strategies.

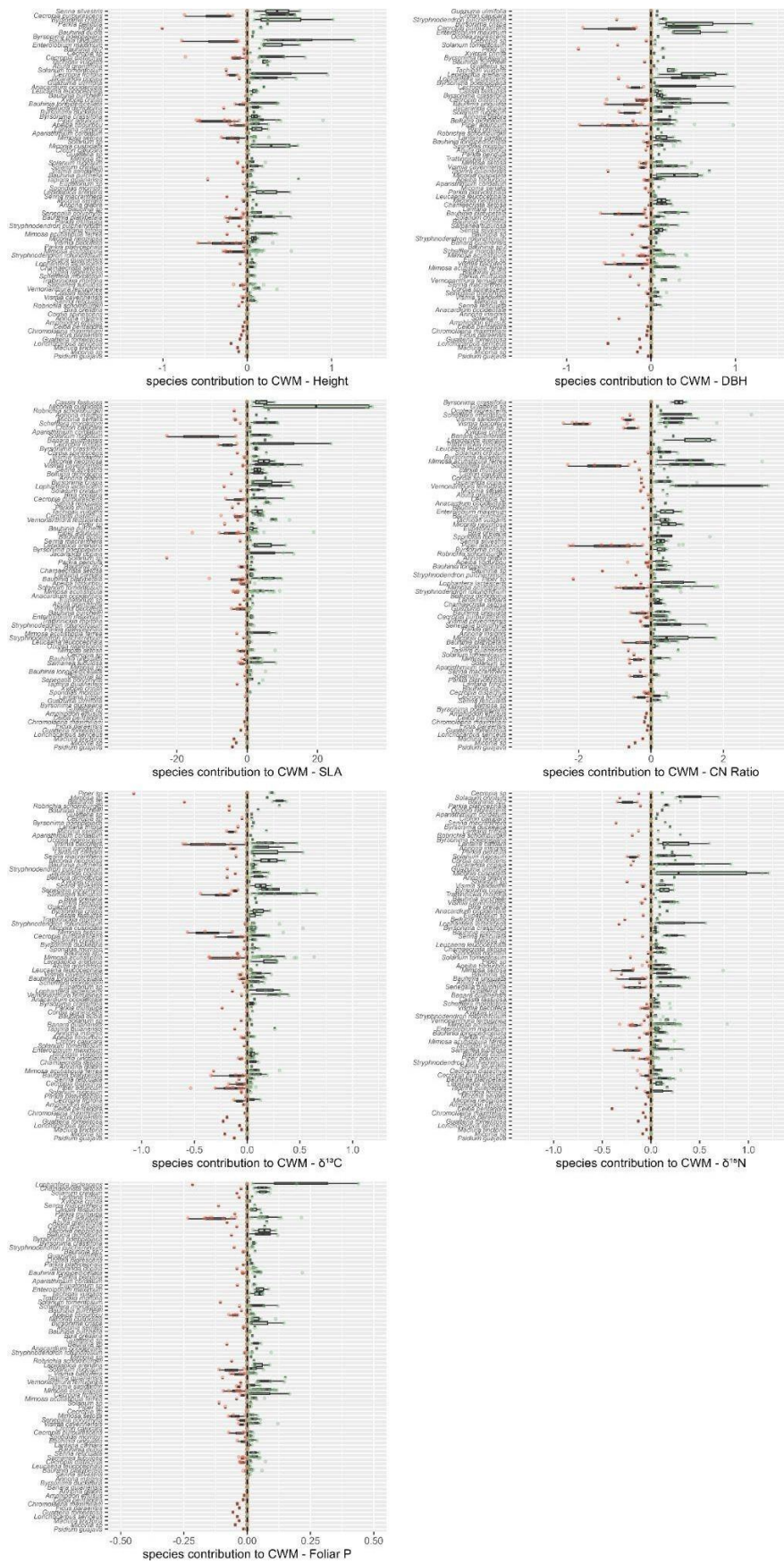


Figure 7 Contribution of species to community-weighted mean (CWM) values of functional traits in invaded (red) and non-invaded (green) rehabilitation sites. Traits include Height, DBH, SLA, C:N ratio, $\delta^{13}\text{C}$, foliar P and $\delta^{15}\text{N}$. Boxplots represent the relative contribution of each species to trait values within their respective communities, while points represent plot-level contribution values. Species are ordered along the y-axis according to their mean functional originality, with more functionally original species at the top and less original species at the bottom.

Native species from rehabilitation sites defined the functional space, which fully encompassed the invasive species across the first three PCoA axes (explaining 61.3% of trait variation) (Figure8). From the nearby protected areas, 92 native species were found to be inside the functional space of rehabilitation sites. The pair-wise comparison between natives and the invasive *M. calabura* showed that the most functional similar native species are from nearby protected areas and from not invaded sites (S3T2). Being the most functional similar the following species from nearby protected area *Matayba arborescens* (0.008), *Tabernaemontana undulata* (0.01), *Mabea fistulifera* (0.011), *Maprounea guianensis* (0.012), *Euterpe precatoria* (0.013), *Abarema cochleata* (0.016) and *Sapium glandulosum* (0.014); species from non-invaded sites *Banara guianensis* (0.013) and *Byrsonima duckeana* (0.015); and the native species found in both invaded and not invaded sites *Bellucia dichotoma* (0.017).

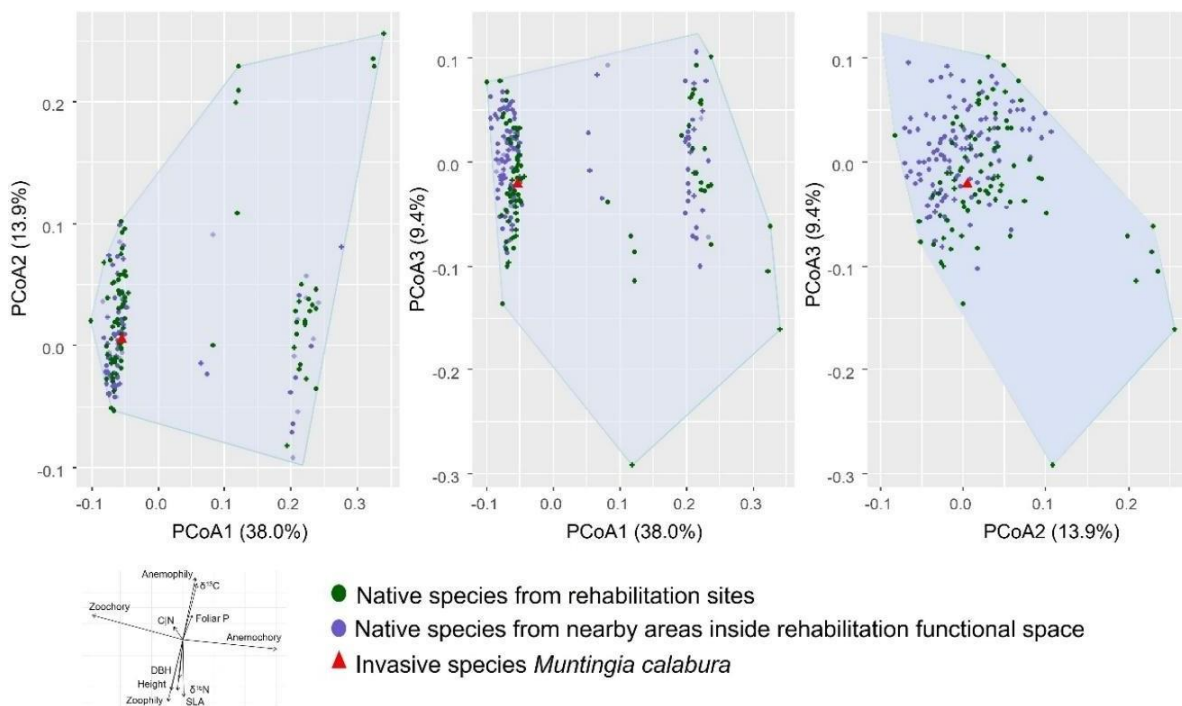


Figure 8 Functional space of native species of rehabilitation sites based on Principal Coordinates Analysis (PCoA) using multiple functional traits. The shaded polygon represents the functional space of native species in rehabilitation sites. Axes represent the first three PCoA dimensions, explaining 38.0%, 13.9%, and 9.4% of the variation, respectively.

The Redundancy Analysis showed significant influence of soil chemical composition in species CWM metrics (ANOVA permutation test, p -value = 0.008), with two first axes explaining 29.9% of the total variation (Figure 9). Among the environmental variables included in the model, Al, Mn, K and P showed the highest tendency to explain the CWM variation (S1T1). Soil properties of invaded and non-invaded sites were different although showed overlap in ordination space (S2F10), with a slight tendency for non-invaded sites to align with higher soil phosphorus values, showing the underlying role of edaphic conditions to structure the functional composition of native woody communities in rehabilitation sites.

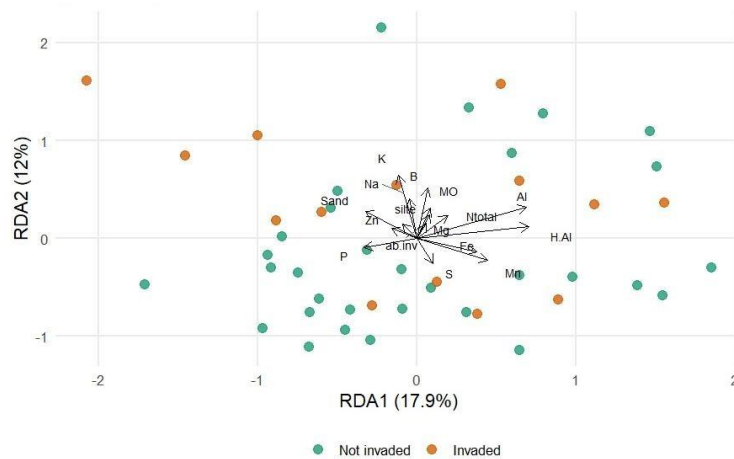


Figure 9 Redundancy Analysis (RDA) relating soil variables to community-weighted mean traits in invaded and non-invaded communities. Environmental vectors represent soil gradients constraining CWM structure. The constrained model was significant according to the ANOVA permutation test ($p = 0.008$).

4.4 Discussion

By examining how an invasive species integrates into post-mining rehabilitation sites, this study provides new insights into the invasion dynamics of *Muntingia calabura* and its effects on the functional structure of native woody communities. Overall, our results indicate that invasion reshaped community functional structure primarily through changes in dominance and trait weighting, rather than through native species loss. Although invaded and non-invaded sites partially overlapped in functional space, invaded sites exhibited reduced functional diversity and a distinct functional composition. These results suggest that invasion by *M. calabura* primarily altered community structure and dominance patterns rather than causing

substantial species loss, highlighting functional restructuring as a key outcome of invasion in rehabilitated systems.

Native functional composition changed with invasion, yet dominant ecosystem functions were maintained, as indicated by similar CWM values between invaded and non-invaded communities. This pattern suggests that the invasive species functionally substitutes native species with comparable trait syndromes, thereby sustaining some ecosystem functions. However, this functional substitution was accompanied by a contraction of the occupied functional space and increased similarity among communities, as reflected by reduced functional richness and functional beta diversity in invaded communities. These patterns are consistent with functional homogenization reported for plant invasions (Tordoni et al., 2019). This occurs because the dominance of the invader appears to replace multiple native contributors, resulting in a simplified functional structure in which ecosystem functioning may be temporarily maintained but functional richness and redundancy are reduced (Wang et al 2022). Such losses are likely to constrain rehabilitation trajectories by limiting the diversity of functional strategies available to buffer environmental variability and future disturbances, ultimately slowing or compromising the recovery of resilient and self-sustaining native communities.

Despite the overall overlap in functional space, invasion altered the relative importance of species contributing to CWM trait values, revealing contrasting mechanisms of functional structuring between invaded and non-invaded communities. In non-invaded areas, functionally more original species tended to contribute more to CWM traits, indicating that functional originality played a key role in structuring community functional composition. For instance, analyses of species contributions to CWM revealed that foliar P was consistently driven by functionally original species in both invaded and non-invaded communities, indicating that relatively small changes in the abundance of these species can strongly influence community-level nutrient traits. In contrast, invaded communities were dominated by a reduced number of species whose contributions to CWM traits showed no consistent relationship with trait originality and were primarily driven by species abundance. As a result, functional composition became increasingly concentrated in fewer species, reshaping not only species composition but also the weighting of functional strategies within communities. This pattern is consistent with the functional homogenization detected in invaded sites and reflects a simplification of functional structure driven by dominance. The decline or absence of functionally original native species, such as *Cassia fastuosa*, *Byrsonima crassifolia*, and *Senna silvestris*, represents a

critical loss of unique trait combinations that influence community-level functional traits. Targeted enrichment planting of these functionally original species in rehabilitated sites may therefore be essential to restore functional heterogeneity, rebalance trait contributions, and enhance the resilience and long-term stability of rehabilitated native communities.

Muntingia calabura was functionally similar to native species, a pattern that likely facilitates its establishment in rehabilitation sites. Post-mining environments are typically shaped by strong environmental filtering, which constrains the range of viable trait combinations and promotes trait convergence among co-occurring species. In this context, some invasive species may succeed by adopting a join-the-local strategy, establishing themselves by matching the functional trait space of resident natives (Gillerot et al. 2021; Lodge et al. 2018; Tecco et al. 2010). We observed that *M. calabura* occurred within the functional space of rehabilitation sites, consistent with a join-the-local strategy. However, while non-invaded sites exhibited a higher diversity of species occupying this space, invaded sites were characterized by fewer species sharing this functional space. This pattern helps explain why functional similarity did not constrain invasion impacts. Instead, invasion by *M. calabura* was associated with reduced functional richness and a reorganization of native species' contributions, demonstrating that invaders matching resident trait profiles can still drive substantial functional restructuring under strong environmental filtering.

Most functionally similar native species to *M. calabura* were found in nearby preserved forests and non-invaded rehabilitation sites, including *Matayba arborescens*, *Tabernaemontana undulata*, and *Maprounea guianensis*. Their presence in rehabilitating sites may increase functional redundancy, which can enhance community resistance to invasion (Funk et al., 2008). In contrast, invaded sites exhibited fewer native species and reduced contributions from key functional dominants. Furthermore, given that dominant species and those with extreme trait values exert strong influence on community functioning, their decline likely amplifies invasion impacts (Ernst et al. 2023). So, reinforcing the presence of native species dominant and/or ones that contribute strongly to functional structure may be essential to restore functional diversity and resilience. In mineland rehabilitated sites in Carajás region, species such as *Miconia cuspidata*, *Byrsonima crispera*, *Enterolobium maximum*, and *Lepidaploa arenaria*, which were important contributors in non-invaded sites, should also be prioritized in rehabilitation sowing to enhance functional diversity.

Our results indicate that soil properties played a key role in explaining functional responses of native plant communities, as expected under the strong environmental filtering

characteristic of post-mining rehabilitation sites (Castro et al. 2022). In such systems, soil constraints strongly limit the range of viable functional strategies, making community functional composition particularly sensitive to variation in edaphic conditions. The invasion by *Muntingia calabura* showed a clear tendency to occur in acidic soils and sandy substrates, consistent with previous studies, (Kehind et al., 2020), highlighting the role of soil properties in both invasion patterns and functional trait distribution. Moreover, some invasive species are known to tolerate but also to alter and benefit from changes in soil nutrient dynamics, thereby enhancing their growth and competitive ability (Castro et al., 2024; Jaafar et al., 2022; Sena-Souza et al., 2023). These effects may arise through modifications in nutrient cycling, changes in microbial activity, or allelopathic interactions that influence nutrient availability and native species performance. Allelopathic effects have already been reported for *M. calabura*, suggesting a potential mechanism through which the species may suppress native recruitment or indirectly modify soil conditions (Wahyuningtyas et al., 2025). However, further experimental studies are needed to assess the direct effects of this species on soil properties and its competitive interactions with native species, particularly in rehabilitated systems where environmental filtering is already strong.

4.5 Conclusion

Our study demonstrates that invasion by *Muntingia calabura* can substantially reshape the functional structure of native woody communities in post-mining rehabilitation sites, even when the invader is functionally similar to resident species. Functional similarity facilitated the establishment and dominance of *M. calabura* under the strong environmental filtering characteristic of rehabilitated systems, yet it did not prevent invasion impacts. Invaded communities exhibited reduced functional richness, altered functional composition, and a reorganization of native species' contributions to community-weighted mean traits, indicating that community structure and the weighting of functional strategies can be modified without pronounced shifts in average trait values. Thus, although ecosystem functions may appear to be maintained, invasion-driven functional homogenization is likely to erode functional diversity, redundancy, and community resilience.

Effective rehabilitation should therefore move beyond the recovery of apparent ecosystem functioning and explicitly aim to restore functional diversity and redundancy. This requires not only controlling invasive species but also strategically reinforcing native species that contribute most to functional structure, including dominant and functionally original

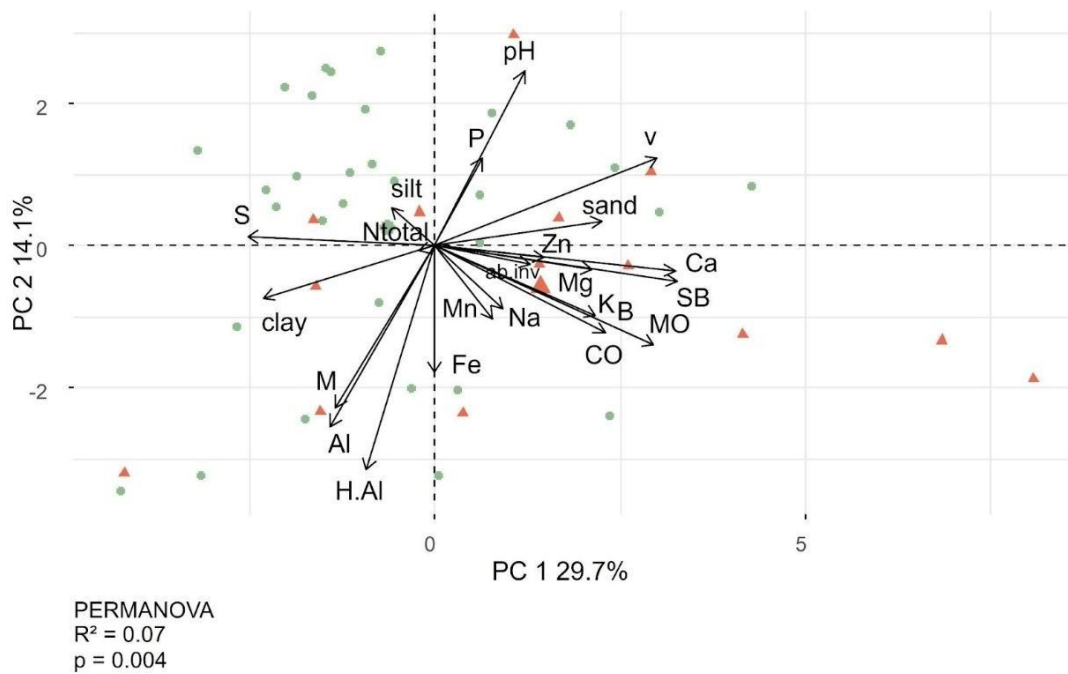
species. Trait-based restoration strategies that account for environmental filtering, soil conditions, and species' functional roles represent a promising framework to promote resilient, self-sustaining native communities in post-mining landscapes, but their effectiveness still requires experimental validation, particularly regarding species performance and long-term functional outcomes.

4.6 Supporting Information

S1. Table 1 Valores médios (\pm desvio padrão) de concentrações de alumínio (Al), manganês (Mn), potássio (K), fósforo (P) e sódio (Na) em parcelas invadidas e não invadidas. Os valores representam variáveis do solo incluídas na análise de redundância (RDA) que relacionou propriedades do solo à abundância da espécie invasora e às métricas funcionais das comunidades nativas. A significância das diferenças entre parcelas invadidas e não invadidas foi avaliada por teste F baseado em permutação

Variable	Invaded (mean \pm SD)	Non-invaded (mean \pm SD)	F-test	p-value
Al	0.032\pm0.053	0.030\pm0.057	4.514	0.004
Mn	99.607\pm59.40	83.102\pm43.57	3.038	0.008
K	33.029\pm8.759	23.897\pm9.461	2.633	0.024
P	10.564\pm5.095	13.974\pm17.138	2.160	0.058
Na	4.282 \pm 2.523	4.853 \pm 4.143	1.832	0.098
H+Al	1.814 \pm 0.488	1.764 \pm 0.558	1.7585	0.127
Zn	2.614 \pm 2.591	2.042 \pm 2.685	1.503	0.167
Fe	17.5 \pm 9.525	18.032 \pm 11.932	1.254	0.250
B	0.104 \pm 0.068	0.072 \pm 0.045	1.204	0.297
MO	2.932 \pm 1.551	1.821 \pm 0.6	1.168	0.309
Ntotal	0.119 \pm 0.062	0.144 \pm 0.154	1.012	0.409
Mg	1.079 \pm 0.634	0.785 \pm 0.859	0.817	0.533
Sand	396.429 \pm 102.59	402.258 \pm 79.36	0.833	0.547
S	27.716 \pm 23.559	29.678 \pm 19.441	0.540	0.762

Invader abundance	7.571±9.921	0.0±0.0	0.523	0.763
Silt	158.929±37.477	145.161±41.038	0.530	0.796



S2.Figure 10 Principal Component Analysis (PCA) biplot of soil physicochemical variables in invaded (red) and non-invaded (green) plots. Points represent sampling plots, and arrows indicate the contribution and direction of soil variables to the ordination axes.

S3. Table 2 Functional distance between the invasive *Muntingia calabura* and the 50 functionally closest native species from nearby protected areas (UC) and from invaded (IN) and non-invaded (NI) rehabilitation sites.

Site	Species name	Functional distance to invader
UC	<i>Matayba arborescens</i>	0.00809535
UC	<i>Tabernaemontana undulata</i>	0.01005526
UC	<i>Mabea fistulifera</i>	0.01078624
UC	<i>Maprounea guianensis</i>	0.01209465
UC	<i>Euterpe precatoria</i>	0.01276314
NI	<i>Banara guianensis</i>	0.01329873
UC	<i>Sapium glandulosum</i>	0.01385691
NI	<i>Byrsonima duckeana</i>	0.01536864
UC	<i>Abarema cochleata</i>	0.01568473
IN-NI	<i>Bellucia dichotoma</i>	0.01708976
NI	<i>Guazuma ulmifolia</i>	0.01806569
NI	<i>Senna silvestris</i>	0.01996662
NI	<i>Parkia pendula</i>	0.02095086
IN-NI	<i>Parkia platycephala</i>	0.02188705
UC	<i>Casearia grandiflora</i>	0.02212776
NI	<i>Trattinnickia burseraefolia</i>	0.02405305
IN	<i>Ficus paraensis</i>	0.02411854
UC	<i>Cordia exaltata</i>	0.02482477
IN-NI	<i>Stryphnodendron pulcherrimum</i>	0.02638374
IN	<i>Lonchocarpus sericeus</i>	0.02722742
UC	<i>Erythroxylum citrifolium</i>	0.02744159
UC	<i>Theobroma speciosum</i>	0.02759224
NI	<i>Miconia cuspidata</i>	0.02940907
UC	<i>Casearia javitensis</i>	0.02961657
IN-NI	<i>Stryphnodendron rotundifolium</i>	0.03148429
UC	<i>Inga stipularis</i>	0.03323701
UC	<i>Inga thibaudiana</i>	0.03333969
UC	<i>Coussarea capitata</i>	0.03376927
IN-NI	<i>Vismia cayennensis</i>	0.03386737
IN-NI	<i>Abuta grandifolia</i>	0.03431095
UC	<i>Astrocaryum gynacanthum</i>	0.03435296
UC	<i>Lacunaria crenata</i>	0.03512661
UC	<i>Pouteria manaosensis</i>	0.03522317
UC	<i>Guatteria punctata</i>	0.03527661
IN-NI	<i>Solanum tomentosum</i>	0.03743468
IN	<i>Guatteria tomentosa</i>	0.03855660
UC	<i>Myrcia bracteata</i>	0.03878095
UC	<i>Xylopia brasiliensis</i>	0.03932053
UC	<i>Garcinia gardneriana</i>	0.03945113
IN-NI	<i>Apeiba tibourbou</i>	0.03975354
UC	<i>Eugenia omisssa</i>	0.04002256
UC	<i>Cordia nodosa</i>	0.04005682
IN-NI	<i>Cordia spinescens</i>	0.04044404
UC	<i>Palicourea guianensis</i>	0.04189794
UC	<i>Licania membranacea</i>	0.04195416
NI	<i>Annona glabra</i>	0.04198358
UC	<i>Xylopia aromatica</i>	0.04209614
UC	<i>Toulicia guianensis</i>	0.04243321
UC	<i>Eugenia punicifolia</i>	0.04500916
UC	<i>Licania canescens</i>	0.04520839

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5. SESSÃO III

Utilização do aprendizado profundo para mapeamento e monitoramento de espécies invasoras em áreas tropicais de recuperação ambiental pós mineração

A terceira sessão desta tese foi submetida na revista Restoration Ecology. A sessão foi elaborada e formatada conforme as normas da publicação científica disponível em:
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Utilização do aprendizado profundo para mapeamento e monitoramento de espécies invasoras em áreas tropicais de recuperação ambiental pós mineração

RESUMO

A detecção e o monitoramento de populações invasoras em áreas em recuperação são etapas fundamentais para o manejo eficaz de espécies exóticas uma vez que permitem avaliar a efetividade das ações de controle e gerar alertas sobre novas invasões. Atrasos na detecção e a ausência de monitoramento contínuo favorecem a proliferação dessas espécies e comprometem o sucesso da restauração ecológica. Nesse contexto, o sensoriamento remoto tem se destacado por permitir a identificação de áreas dominadas por espécies invasoras, enquanto o uso de aprendizado profundo, especialmente redes neurais convolucionais (CNNs), automatiza a análise de imagens e aumenta a precisão na identificação. O objetivo deste trabalho foi aplicar uma metodologia automatizada para a classificação da espécie invasora *Muntingia calabura* L. (Muntingiaceae) em áreas de recuperação ambiental na região de Carajás, Amazônia Oriental, por meio da análise de imagens de alta resolução e segmentação via redes neurais convolucionais. Para isso, duas áreas de recuperação foram utilizadas para o estudo, a pilha de estéril Sul 4 foi selecionada para o treinamento e validação, e a Oeste foi utilizada como área teste do modelo. O treinamento foi realizado com validação cruzada K-Fold ($n = 5$), durante até 100 epochs por fold, com batch size de 32. A escolha do modelo final baseou-se no desempenho de validação, sendo selecionado o modelo do fold 2, que apresentou a menor perda (0,095) e a maior acurácia (0,965). A validação dos resultados foi realizada por meio de matriz de confusão e métricas de desempenho (acurácia, precisão, sensibilidade e F1-score), com 5.000 pontos amostrados aleatoriamente. Na área de treinamento, o modelo alcançou acurácia de 97% e F1-score de 0,92 para a classe da espécie invasora. Os mapas de predição revelaram distribuição não aleatória da espécie, com formação de áreas homogêneas ao longo dos taludes da pilha, indicando padrão de expansão linear e comportamento excludente. A aplicação do modelo em área teste não utilizada no treinamento evidenciou sua capacidade de generalização, com acurácia de 98% e F1-score de 0,95 para a classe invasora. As predições revelaram padrão espacial semelhante ao da área de treinamento, com maior ocorrência em ambientes abertos e baixa concorrência com outras espécies, reforçando o potencial da abordagem como ferramenta para o monitoramento contínuo e direcionamento de estratégias de controle em áreas de recuperação ambiental.

Palavras-chave: Aprendizado profundo, espécies invasoras, mapeamento espacial

5.1 Introdução

O manejo de espécies vegetais invasoras na recuperação de áreas degradadas representa um dos principais desafios para restauração dos serviços ecossistêmicos a longo prazo (Weidlich et al., 2020). Entre as práticas de manejo, o monitoramento periódico das populações invasoras é crucial para acompanhar sua distribuição, dispersão para novas áreas e avaliar a eficácia das estratégias de controle (Castro et al., 2023; Young et al., 2022). Tradicionalmente, esse monitoramento é realizado por meio de visitas a campo e marcação de indivíduos, métodos que demandam tempo, elevam custos operacionais e dificultam o acompanhamento em larga escala, favorecendo a proliferação das espécies. Diante desse cenário, o sensoriamento remoto surge como uma solução promissora, permitindo a detecção e o mapeamento de alvos específicos com maior eficiência e precisão (Bolch et al., 2020; Bzdęga et al., 2021; Fricke; Olden, 2023; Oldeland et al. 2021).

A principal limitação no monitoramento de espécies invasoras em projetos de recuperação é a detecção precoce e o acompanhamento contínuo em grandes áreas. Com os avanços do sensoriamento remoto, diversas iniciativas têm sido desenvolvidas para detectar e mapear espécies vegetais invasoras de forma remota (e.g. Bzdęga et al., 2021; Dash et al., 2019; Lehmann et al., 2017; Martinez et al., 2019; Paz-Kagan et al., 2019). Nesse caso, a distinção entre as espécies invasoras e nativas baseia-se principalmente nas características intrínsecas das plantas, como composição química, estrutura foliar, texturas e padrões fenológicos, que influenciam a reflectância detectada por sensores remotos (Colwell, 1974; Kumar; Karne, 2017, Weisberg et al. 2021). Embora essas abordagens tenham alcançado um desempenho satisfatório, sua automatização é um desafio devido à necessidade de conhecimento das propriedades biológicas específicas da espécie-alvo e à escolha das características adequadas para uma boa classificação.

No contexto do sensoriamento remoto, as redes neurais convolucionais (CNNs) vêm se destacando como uma abordagem promissora para a classificação automática de imagens. Esses algoritmos de aprendizado profundo processam dados visuais de forma hierárquica, extraíndo padrões de textura, forma e cor relevantes para a diferenciação entre espécies (Gu et al., 2018). As CNNs utilizam camadas convolucionais que aplicam filtros ajustáveis por meio de operações de convolução, nas quais cada pixel é combinado com os filtros para gerar mapas de atributos que destacam informações discriminantes para a identificação do objeto de interesse (Chollet & Allaire, 2018). Esses filtros são ajustados gradualmente durante o treinamento, reduzindo erros e refinando a detecção automaticamente durante o treinamento do modelo (Alzubaidi et al., 2021). Entre suas arquiteturas, a U-Net, originalmente desenvolvida para

segmentação biomédica (Ronneberger et al. 2015), tem destaque na segmentação pixel a pixel, preservando a localização espacial dos alvos e aumentando a precisão da classificação. Sua capacidade de detectar padrões mesmo diante de variações de posição, orientação e escala tem impulsionado seu uso no mapeamento de vegetação em ambientes complexos (Dash et al. 2019; James & Bradshaw, 2020; Kolhar & Jagtap, 2021). Ao proporcionar análises detalhadas e escaláveis, as CNNs representam uma abordagem inovadora para mapear a distribuição e a dinâmica das populações invasoras, superando limitações associadas à seleção manual de características discriminantes (Amarasingam et al. 2024; Lamba et al., 2019). No entanto, apesar do grande potencial dessas tecnologias, sua aplicação em regiões megadiversas, como a Amazônia, ainda é limitada, destacando a necessidade de estudos que explorem sua eficácia nesses contextos desafiadores.

O crescente acesso a veículos aéreos não tripulados equipados com câmeras de alta resolução tem viabilizado a captura de imagens detalhadas em áreas extensas, ampliando as possibilidades de detecção remota de espécies vegetais em larga escala (Bolch, et al. 2020; Miyoshi et al. 2020). Isso porque a reconstrução tridimensional do terreno gera mapas com detalhamento espacial, espectral e temporal que captura diferenças na morfologia e nos padrões foliares entre as espécies (Dash et al. 2019). Ao aproveitar as informações espaciais e espectrais fornecidas por essas imagens, as CNNs podem discriminar eficazmente espécies vegetais e tipos de cobertura do solo, facilitando um mapeamento mais detalhado e abrangente da distribuição e dinâmica de espécies, incluindo as invasoras, mesmo em ambientes complexos (Amarasingam et al. 2024; Cruz et al. 2023). Diante disso, o objetivo desse trabalho foi aplicar uma metodologia automatizada para a classificação da espécie invasora *Muntingia calabura* L. (Muntingiaceae) em áreas de recuperação ambiental na região de Carajás, Amazônia Oriental, por meio da análise de imagens de alta resolução e segmentação via redes neurais convolucionais.

5.2 Materiais e Métodos

5.2.1 Área de estudo

O estudo foi conduzido em áreas de recuperação ambiental pertencentes ao complexo de mineração de ferro da Vale, localizadas na Floresta Nacional de Carajás (Figura 11). Essas áreas de recuperação correspondem a áreas de deposição de estéril de mina, um material inerte, não tóxico e sem valor econômico, disposto de forma sistemática em taludes e bermas, resultando na formação de pilhas artificialmente construídas. As pilhas do Complexo N4-N5 são compostas por um material geologicamente heterogêneo, oriundo de diferentes frentes de lavra das minas que integram o Complexo Vale Ferrosos Carajás.

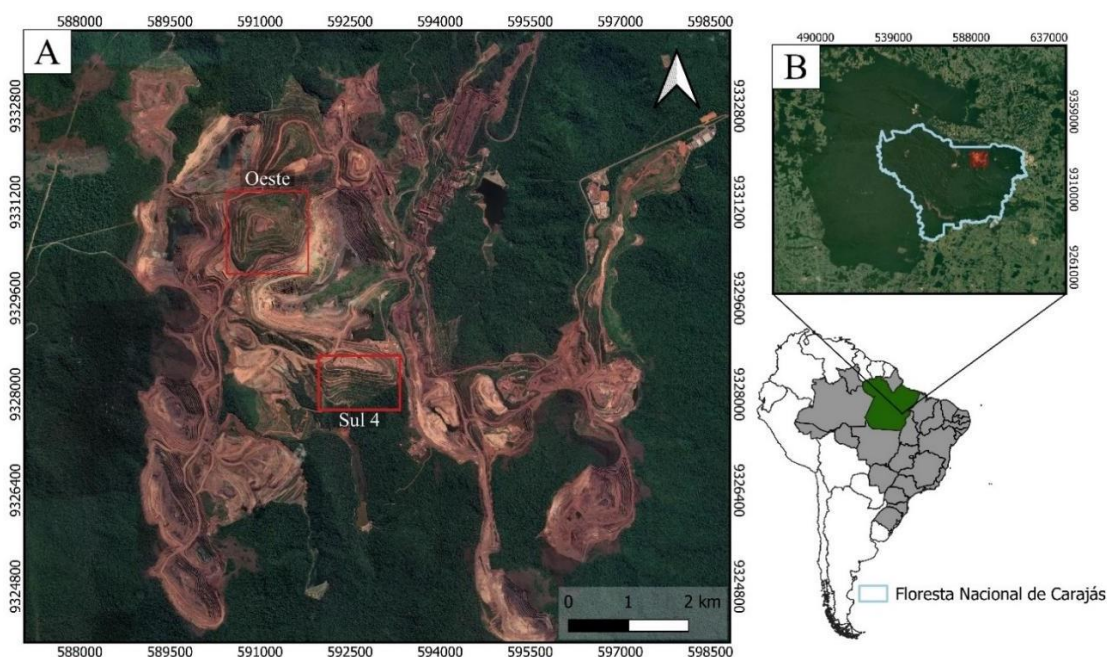


Figura 11 Mapa da área de estudo. Em destaque as pilhas de estéril em recuperação ambiental utilizadas para o treinamento do modelo (Sul 4) e validação do modelo (Oeste), os quais foram gerados os mapas de classificação.

Seguindo os protocolos operacionais da área, as pilhas de estéril recebem correção do solo (alcalinização) e hidrossemeadura com uma mistura de sementes de espécies nativas e exóticas não invasoras de rápido crescimento. Juntamente a semeadura, são aplicados fertilizantes e um composto aplicado para aumentar a aderência das sementes nos taludes devido à sua inclinação (Gastauer et al., 2022). Embora não sejam semeadas, espécies invasoras têm se estabelecido nessas áreas (Giulietti et al., 2018) (Figura 12), apesar da ausência de dados precisos sobre sua distribuição espacial e tamanho populacional. Considerando a necessidade

de favorecer o desenvolvimento da vegetação nativa e os impactos negativos causados por espécies invasoras (Hess, Mesléard & Buisson, 2019), os programas de recuperação e monitoramento incluem estratégias específicas para o seu controle. Entre as práticas mais comuns, a capina manual e controle químico são realizados de forma pontual em locais onde a presença dessas espécies já foi registrada (Weidlich et al., 2020).

Dentre as espécies invasoras mais problemáticas na região, destaca-se a arbustiva *Muntingia calabura* L. (Muntingiaceae) (Gastauer et al., 2022; Giulietti et al., 2018). Essa espécie apresenta elevada produção de sementes, rápido crescimento e capacidade de formar populações dominantes nas áreas em recuperação (Fleming et al., 1985; Figueiredo et al., 2008; Martins et al., 2017; Silva, Martins & Balestrin, 2021). Embora a maioria dos estudos sobre *M. calabura* apresentem foco em suas propriedades bioquímicas e aplicações farmacológicas (Seixas, Palermo & Rodrigues, 2021), ela já foi apontada como uma espécie com potencial invasor devido a seus efeitos alelopáticos (Figueiredo et al., 2008; Gastauer et al., 2022). O monitoramento de sua presença na região é uma necessidade urgente, dado que ainda não se conhece a real extensão de suas populações nem seu status de expansão. Essa lacuna é especialmente preocupante diante do risco de novas invasões em áreas naturais protegidas adjacentes.



Figura 12 Espécie arbustiva *Muntingia calabura*, invasora e problemática na recuperação das pilhas de estéril do complexo N4-N5.

Duas pilhas de estéril foram utilizadas para o desenvolvimento e avaliação do modelo de classificação da espécie invasora (Figura 13). A seleção de duas áreas está baseada na necessidade de treinar e validar o modelo em uma área e testar sua performance em outra não treinada, o que permite avaliar o poder de generalização do modelo e verificar sua eficácia na classificação. Assim, a pilha de estéril Sul 4 foi utilizada como área de treinamento e validação para a construção do modelo, enquanto a pilha de estéril Oeste foi utilizada como a área teste, permitindo avaliar o desempenho final do modelo em uma região distinta, após seu treinamento e ajuste.

5.2.2 Coleta de dados

5.2.2.1 Captura de imagens e produção do ortomosaico

As imagens das pilhas de estéril Sul 4 e Oeste foram adquiridas por meio de levantamentos aéreos realizados com um veículo aéreo não tripulado (VANT) DJI Mavic 3 M, equipado com câmeras RGB e multiespectral, além de um sistema de georreferenciamento por GPS com correção em tempo real (RTK). O sistema de coordenadas adotado para o georreferenciamento foi o WGS 84 / UTM zona 22S (EPSG:32722), assegurando a compatibilidade com análises geoespaciais subsequentes.

As imagens foram amostradas em setembro de 2023 nas pilhas de estéril Sul 4 e Oeste, coletadas em dia ensolarado de poucas nuvens. Para garantir a completa cobertura das áreas de estudo, foram realizados voos automatizados sobre uma área de 73,3 ha na pilha de estéril Sul 4, resultando na captura de 18.532 imagens. Para a pilha de estéril Oeste, a área mapeada foi de 92 ha. Os voos foram planejados com uma altitude média de 55,3 metros, com sobreposição de imagens de 80% no sentido frontal e 70% lateral, parâmetros considerados adequados para a geração de produtos fotogramétricos de alta resolução.

O software Agisoft Metashape foi utilizado para a criação do ortomosaico. Nesse processo, inicialmente foi realizado o georreferenciamento e o alinhamento das fotos, seguido pela geração da nuvem densa de pontos, que é um conjunto de pontos georreferenciados necessários para recriar a superfície do terreno. A nuvem densa gerada continha um total de 66.693.046 pontos, distribuídos em uma resolução espacial que resultou em um modelo digital de superfície (DSM) de dimensões 14.118 x 8.166 pixels.

A partir dessa nuvem densa, foi gerado o modelo digital de superfície com uma resolução de 6,29 cm/pixel e densidade de 253 pontos/m². Por fim, o ortomosaico foi construído com base

nos dados de superfície, utilizando o modo de mesclagem "mosaic" (blend mode). Esse modo permitiu selecionar as partes das imagens que melhor representavam a superfície mapeada, resultando em um mosaico contínuo com resolução espacial de 2.65 cm de alta qualidade.

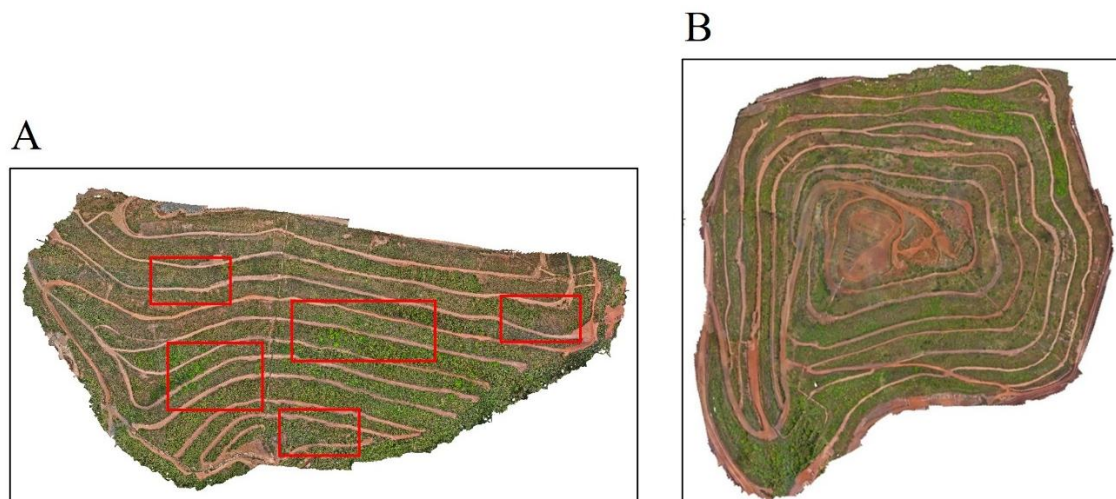


Figura 13 Ortomosaicos da pilha de estéril Sul 4 (A), área de treinamento e validação do modelo; e da pilha de estéril Oeste (B) produzido a partir das imagens coletadas durante sobrevôo

5.2.2.2 Preparação das amostras e estratégias para otimização do modelo

A pilha de estéril Sul 4 foi selecionada como área de treinamento e validação do modelo, com base na ocorrência conhecida da espécie *Muntingia calabura*. A coleta de dados foi realizada em cinco pontos distintos dentro da pilha (Figura 13), selecionados para representar adequadamente a variabilidade visual da vegetação-alvo e do fundo.

As amostras foram geradas a partir de imagens RGB, recortadas em blocos de 224×224 pixels, acompanhadas de rasters rotulados. A rotulagem foi realizada manualmente no software QGIS, por meio da vetorização de polígonos sobre as imagens, classificando os pixels em duas categorias: *Muntingia calabura* e fundo (Figura 14). Esse processo resultou em um total de 12.410 amostras anotadas, compostas por imagens RGB e imagens rasterizadas rotuladas. A amostragem foi conduzida com base em pontos de ocorrência confirmada da espécie, garantindo que as regiões escolhidas incluíssem uma diversidade representativa tanto da vegetação de interesse quanto do fundo (a exemplo de solo exposto, outras espécies e sombras). Essa abordagem visou aumentar a robustez do modelo ao lidar com variações da paisagem.

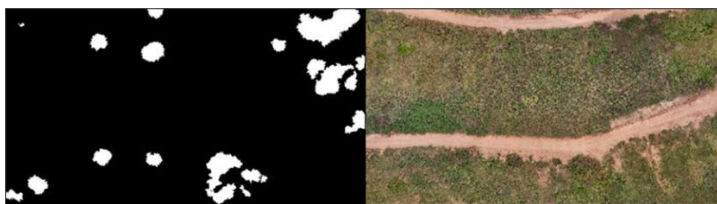


Figura 14 Exemplificação de uma área utilizada para criação de amostras antes do recorte de 224 x 224 pixels. A imagem da esquerda mostra a área em raster com o rótulo (invasora -1, e fundo -0) delimitando a espécie invasora em branco. A direita a área raster RGB.

A precisão de classificação durante uma tarefa em algoritmos de aprendizado profundo depende fortemente da quantidade e da qualidade dos dados de treinamento. De modo geral, esses algoritmos exigem um grande volume de dados para minimizar problemas como o sobreajuste (*overfitting*), que ocorre quando o modelo se torna especialista nos dados de treinamento, reduzindo seu poder de generalização para novos dados. Para mitigar esses problemas, adotamos duas estratégias para otimizar o desempenho do modelo. A primeira foi o aumento de dados, que visa expandir o número de amostras de treinamento por meio de transformações aleatórias nas imagens, como ajustes de brilho, saturação e rotação (Chollet & Allaire, 2018; Perez & Wang, 2017). Neste trabalho, aplicamos o aumento de dados relacionado a saturação, brilho e contraste nas imagens RGB, além de flips horizontais e verticais tanto para as imagens RGB quanto para os rasters rotulados.

A segunda estratégia adotada foi a extração de características por transferência de aprendizado, que permite aproveitar o conhecimento prévio de modelos treinados em grandes bases de dados para acelerar e melhorar o treinamento em novas tarefas. Essa abordagem explora o fato de que as camadas iniciais de redes profundas extraem padrões visuais genéricos como bordas, texturas e formas (Chollet & Allaire, 2018; Kaya et al., 2019). Para este estudo, utilizamos o modelo VGG16 (Visual Geometry Group 16), reconhecido por seu desempenho em classificação de imagens. O VGG16 foi originalmente treinado no banco de dados ImageNet, contendo cerca de 1,2 milhão de imagens anotadas distribuídas em 1.000 classes (Simonyan & Zisserman, 2014), alcançando uma acurácia de 92,7%, sendo uma das principais referências para transferência de aprendizado em visão computacional.

Nesse trabalho, utilizamos as 15 primeiras camadas do VGG16, mantendo congeladas as camadas do chamado bloco 1 durante o treinamento a fim de preservar os pesos previamente otimizados. Dessa forma, o modelo manteve sua capacidade de extrair características visuais genéricas, enquanto as camadas superiores foram ajustadas especificamente para a classificação das amostras relacionadas à espécie invasora *Muntingia calabura*.

5.2.3 Implementação do modelo e treinamento

5.2.3.1 Estrutura do modelo CNN

O aprendizado profundo é um ramo do aprendizado de máquina que utiliza redes neurais artificiais para processar grandes volumes de dados. Nessa abordagem, o aprendizado de padrões ocorre por meio de transformações progressivas dos dados, onde cada camada da rede neural extrai características cada vez mais complexas (Lecun; Bengio; Hinton, 2015). Redes neurais são modelos computacionais inspirados no funcionamento do cérebro humano, compostos por camadas de neurônios interconectados por pesos sinápticos (Chollet & Allaire, 2018). A partir de dados brutos de entrada, como imagens, cada camada transforma a representação original, destacando informações relevantes para a classificação e ignorando detalhes menos importantes. De forma semelhante ao sistema visual humano, as primeiras camadas extraem características genéricas, como bordas, texturas e formas simples, enquanto as camadas mais profundas aprendem padrões complexos e abstratos (Lecun; Bengio; Hinton, 2015). Entre os algoritmos de aprendizado profundo, as redes neurais convolucionais (CNNs) destacam-se por sua eficácia no reconhecimento de objetos em imagens. Essas redes utilizam camadas convolucionais em cascata para extrair informações espaciais e espectrais, resultando em modelos robustos para tarefas de classificação e detecção (Gupta; Pathak; Kumar, 2022).

Para a tarefa de classificar a espécie *Muntingia calabura* nas áreas de recuperação, a CNN foi construída com base na arquitetura U-Net (Figura 15), combinada com extração de características via transferência de aprendizado. A escolha pela U-Net se deve à sua eficácia comprovada em tarefas de segmentação, nas quais a classificação ocorre em nível de pixel (Ronneberger et al., 2015; Kolhar & Jagtap, 2021). Essa arquitetura é composta por duas partes principais: a etapa de contração (*encoder*), responsável pela extração das características, e a etapa de expansão (*decoder*), encarregada de reconstruir a dimensão espacial da imagem e realizar a segmentação.

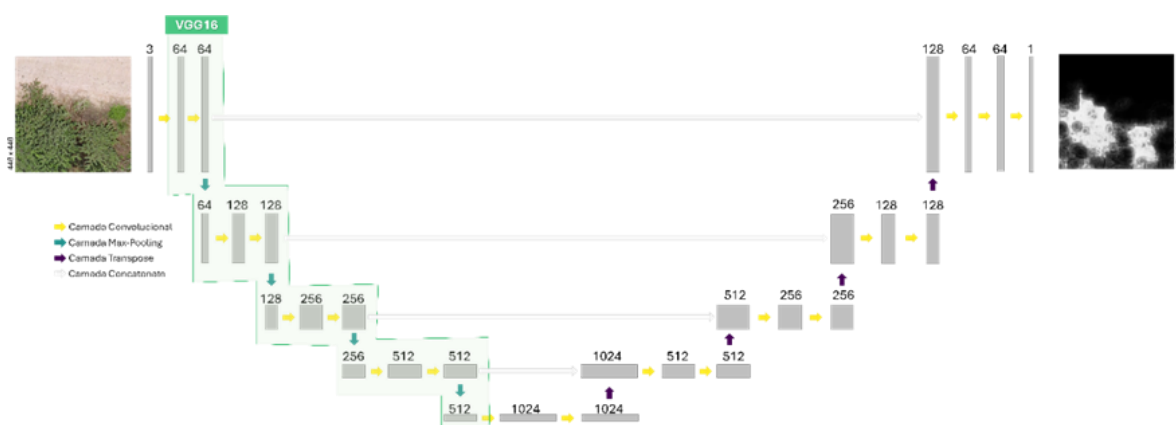


Figura 15 Esquema visual exemplificando a arquitetura U-net do modelo criado para o estudo, com a utilização de camadas do modelo pré-treinado VGG-16 (destaque em verde) e os tipos de camadas criados para construção da rede, em que: setas amarelas indicam as camadas convolucionais, setas verdes as max-pooling, setas roxas as camadas transpose e setas cinzas as concatenar). Os Números acima de cada bloco indicam o número de filtros aplicados em cada camada.

A estrutura da rede foi definida de forma sequencial, com adição progressiva das camadas (Tabela 3). Durante a fase de codificação, a quantidade de filtros foi aumentada gradualmente, enquanto na fase de decodificação ocorreu uma redução simétrica, seguindo o padrão da arquitetura VGG16, utilizada como base para a extração inicial de características. Essa configuração permite capturar representações hierárquicas na codificação e reconstruí-las com precisão durante a decodificação.

Em relação às configurações da rede, as camadas convolucionais e convolucionais transpostas foram configuradas com filtros de tamanho 3×3 e função de ativação ReLU. A camada final utilizou a função de ativação Sigmoid, resultando em um mapa de probabilidade binário voltado à segmentação da espécie invasora. Para preservar as dimensões originais das imagens ao longo do processo de convolução e reconstrução, foi aplicada a técnica de padding em todas as camadas. Além disso, foram incorporadas conexões de atalho (skip connections) entre camadas correspondentes do *encoder* e do *decoder*, com o objetivo de preservar detalhes espaciais finos durante a reconstrução da imagem segmentada.

A Tabela 2 e a Figura 15 e Figura 16 apresentam a estrutura esquemática completa do modelo, detalhando os tipos de camadas utilizadas, incluindo: convolucionais, max-pooling, convolucionais transpostas e conexões de atalho.

Tabela 2 Configurações da rede neural convolucional. Camadas convolucionais: número de filtros convolucionais|tamanho dos filtros convolucionais|função de ativação; Camadas Max-pooling: tamanho do pooling|stride; Camada convolucional transposta: número de filtros|tamanho dos filtros convolucionais|stride

Camada	CNN
VGG16 - Convolucional L1	64 3x3 ReLu
VGG16 - Convolucional L2	64 3x3 ReLu
VGG16 – Max-pooling L1	2x2 2
VGG16 - Convolucional L3	128 3x3 ReLu
VGG16 - Convolucional L4	128 3x3 ReLu
VGG16 – Max-pooling L2	2x2 2
VGG16 - Convolucional L5	256 3x3 ReLu
VGG16 - Convolucional L6	256 3x3 ReLu
VGG16 - Convolucional L7	256 3x3 ReLu
VGG16 – Max-pooling L3	2x2 2
VGG16 - Convolucional L8	512 3x3 ReLu
VGG16 - Convolucional L9	512 3x3 ReLu
VGG16 - Convolucional L10	512 3x3 ReLu
VGG16 – Max-pooling L4	2x2 2
Convolucional L1	1024 3x3 ReLu
Convolucional L2	1024 3x3 ReLu
Convolucional transposta L1	512 2x2 2
Convolucional L3	512 3x3 ReLu
Convolucional L4	512 3x3 ReLu
Convolucional transposta L2	256 2x2 2
Convolucional L5	256 3x3 ReLu
Convolucional L6	256 3x3 ReLu
Convolucional transposta L3	128 2x2 2
Convolucional L7	128 3x3 ReLu
Convolucional L8	128 3x3 ReLu
Convolucional transposta L4	64 2x2 2
Convolucional L9	64 3x3 ReLu
Convolucional L10	64 3x3 ReLu
Convolucional L11	1 1x1 Sigmoid

5.2.3.2 Configurações de hiperparâmetros e treinamento do modelo

Após a definição da arquitetura da rede descrita na seção anterior, o modelo foi implementado e treinado utilizando os pacotes ‘Keras’ e ‘TensorFlow’ (Abadi et al. 2016). Nesta etapa, foram configurados os principais hiperparâmetros responsáveis por direcionar o processo de aprendizado, incluindo a função de perda, o otimizador, a taxa de aprendizado e o número de épocas (*epochs*). Esses parâmetros determinam a forma como o modelo ajusta seus pesos a cada iteração, influenciando diretamente a eficácia do treinamento, a velocidade de convergência e a capacidade de generalização para novos dados. Neste estudo, utilizou-se o otimizador Adam com taxa de aprendizado de 1e-5, enquanto a função de perda adotada foi a entropia cruzada binária (*binary cross-entropy*), apropriada para tarefas de segmentação com duas classes.

O modelo U-Net construído foi treinado utilizando validação cruzada do tipo K-Fold ($k = 5$), com o objetivo de obter uma avaliação mais robusta e confiável da performance geral.

Esse método de reamostragem dividiu o conjunto de dados em cinco folds utilizando partes diferentes do banco de dados para a validação ao longo do treinamento. Cada fold foi treinado por até 100 épocas, com batch size de 32 amostras. Durante o treinamento, as métricas de perda e acurácia foram monitoradas continuamente tanto para o conjunto de treinamento quanto para o de validação. Para mitigar o risco de sobreajuste (overfitting), foram utilizados dois mecanismos: a técnica de Early Stopping, com paciência de 10 épocas, e o ModelCheckpoint, responsável por salvar automaticamente o melhor modelo de cada fold com base na menor perda de validação registrada (Chollet et al., 2015; Goodfellow et al., 2016; Prechelt, 1998).

Ao final do processo, os históricos de desempenho de cada fold foram analisados e o modelo com menor perda e maior acurácia de validação foi selecionado como o modelo final. Em seguida, a função ‘predict’ foi utilizada para gerar o mapa de predições da área de estudo correspondente à pilha de estéril Sul 4.

5.2.3.3 Área de teste do modelo

Utilizamos a pilha de estéril Oeste para avaliar a performance final do modelo e seu poder de generalização, definida como área teste. Esta área foi mantida totalmente independente do processo de treinamento e validação, funcionando como um conjunto externo de dados para mensurar a capacidade do modelo em aplicar o aprendizado a novas regiões.

O ortomosaico da PDE Oeste (Figura 4) foi segmentado em sub-imagens de 224×224 pixels, compatíveis com o formato utilizado para o treinamento do modelo. Em seguida, a função ‘predict’ foi aplicada a essas sub-imagens para gerar o mapa de predição da ocorrência da espécie invasora *Muntingia calabura* na pilha de estéril Oeste. Essa abordagem permitiu a simulação de um cenário prático de aplicação do modelo, avaliando sua eficácia em uma área com condições visuais potencialmente distintas daqueles presentes na área de treinamento (PDE Sul 4).

5.2.4 Avaliação da qualidade do modelo

A qualidade das predições do modelo foi avaliada por meio da construção de matrizes de confusão, uma técnica amplamente utilizada em tarefas de classificação para comparar as predições do modelo com os dados reais. Essa comparação é realizada por meio da quantidade

de:

- Verdadeiros Positivos (VP): número de pixels corretamente classificados como o alvo;
- Falsos Positivos (FP): número de pixels incorretamente classificados como alvo;
- Verdadeiros Negativos (VN) (número de pixels corretamente classificados como não-alvo); e
- Falsos Negativos (FN): número de pixels incorretamente classificados como não alvo.

Para a construção das matrizes, foi adotado um limiar de probabilidade de 0,2 como critério de decisão. Assim, predições com valores iguais ou superiores a 0,2 foram consideradas como presença da espécie invasora *Muntingia calabura*, enquanto valores inferiores foram classificados como fundo.

Duas matrizes de confusão foram geradas para a avaliação do modelo. A primeira foi construída com base em 5.000 pontos aleatórios distribuídos na área de treinamento (PDE Sul 4), cujas classes reais foram determinadas por interpretação visual. A segunda matriz considerou 5.000 pontos aleatórios na área de teste (PDE Oeste), também validados por inspeção visual. Essa segunda matriz foi essencial para avaliar a capacidade de generalização do modelo em uma área não utilizada durante o treinamento, com condições visuais possivelmente distintas. Com base nessas matrizes, foram calculados quatro métricas amplamente utilizadas para avaliação de modelos de classificação: Ambas as análises consideraram como acerto os casos em que a classe real e a classe predita coincidem, permitindo o cálculo de métricas da qualidade de classificação do modelo. A primeira métrica calculada foi a de acurácia, que informa sobre a proporção total de classificações corretas, conforme mostra equação abaixo;

$$Acurácia = \frac{(VP + VN)}{(VP + FP + VN + FN)}$$

A segunda métrica é a de Precisão, que indica a confiabilidade das predições positivas, ou seja, a proporção de predições positivas que são corretas.

$$Precisão = \frac{VP}{(VP + FP)}$$

A terceira métrica é a de Sensibilidade que mede a capacidade do modelo em identificar corretamente os pixels positivos reais.

$$\text{Sensibilidade} = \frac{VP}{(VP + FN)}$$

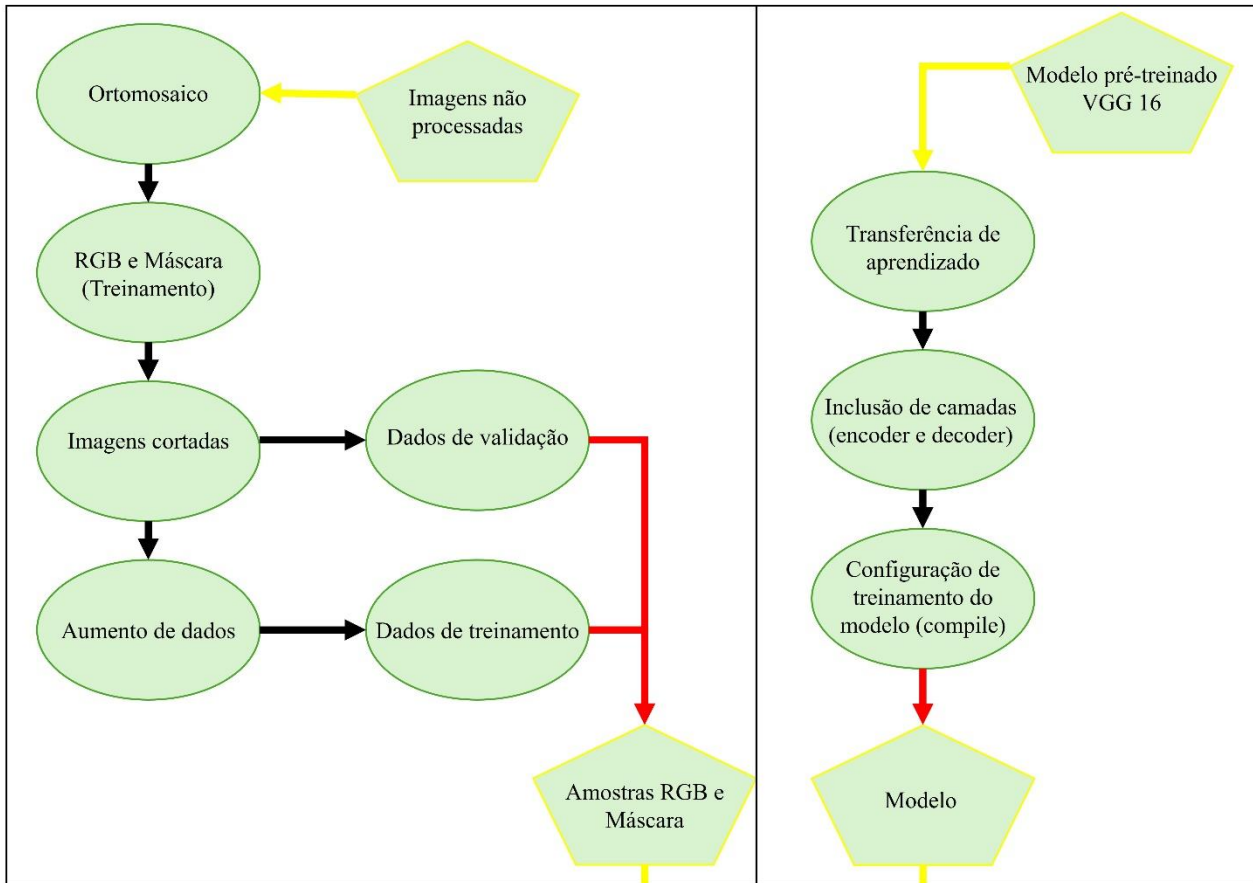
Por fim, também calculamos o F1-Score, que é a média entre precisão e sensibilidade, proporcionando uma medida balanceada da performance.

$$F1 = S * \frac{(\text{Precisão} * \text{Sensibilidade})}{(\text{Precisão} + \text{Sensibilidade})}$$

Essas métricas oferecem uma visão abrangente da performance do modelo, considerando tanto sua capacidade de detectar corretamente a espécie invasora quanto de evitar falsos positivos. A análise integrada desses indicadores permite uma avaliação robusta da eficácia do modelo para aplicações práticas de monitoramento ambiental e tomada de decisão no controle de espécies invasoras.

1. Preparação das amostras

2. Construção do modelo



3. Treinamento do modelo

4. Predição

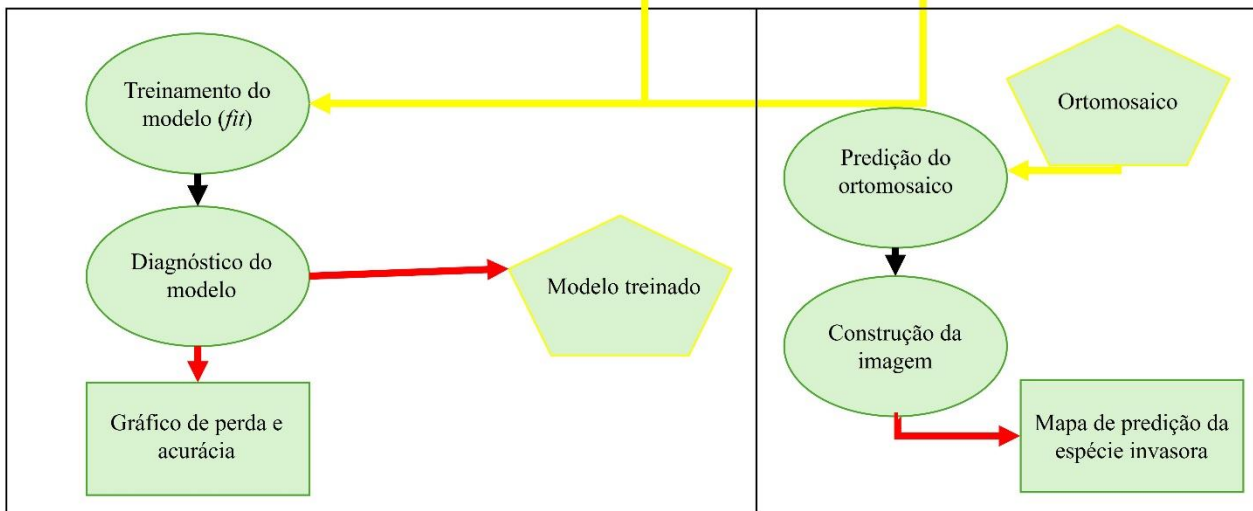


Figura 16 Fluxograma das etapas metodológicas para o mapeamento da espécie invasora *Muntingia calabura* a partir de ortomosaicos de alta resolução. O processo inclui: (1) preparação das amostras (recorte das imagens e aumento de dados), (2) construção do modelo de segmentação baseado em U-Net com transferência de aprendizado a partir do modelo pré-treinado VGG16 neural network architecture, (3) treinamento e avaliação do modelo e (4) predição no ortomosaico para geração do mapa de ocorrência da espécie. As setas indicam entradas (input), etapas de processamento e saídas (output).

5.3 Resultados

A evolução da função de perda ao longo do treinamento não apresentou tendência de curva em formato de U sobre os resultados de validação, indicando que a rede não teve um ajuste excessivo aos dados de treinamento (Figura 17). Os diagnósticos de perda e acurácia durante o treinamento indicaram a parada por volta da época 25, onde a validação média de perda foi de 0.12 e de acurácia de 0.96.

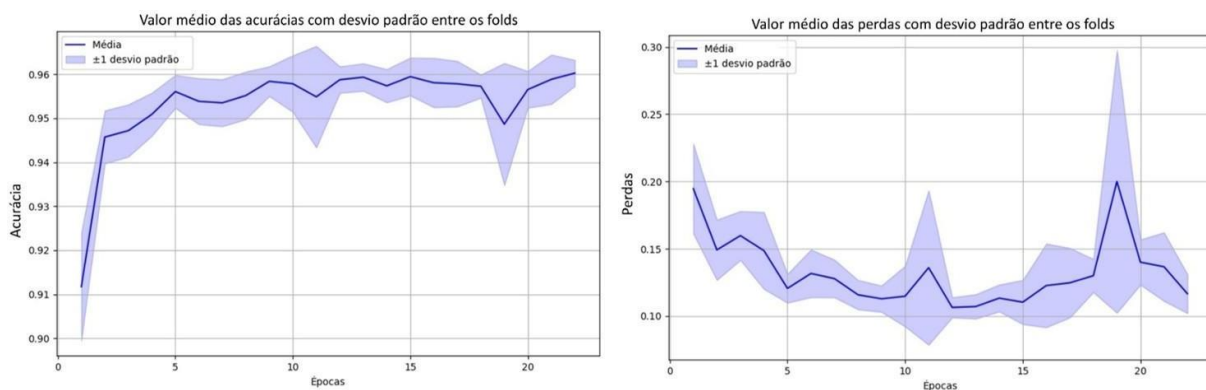


Figura 17 Curvas médias de acurácia (acima) e perda (abaixo) de validação ao longo das épocas, considerando os cinco folds da validação cruzada. As áreas sombreadas representam o intervalo de ± 1 desvio padrão, indicando a variação entre os folds e a estabilidade.

Para a seleção do melhor modelo entre os gerados em cada fold, foram avaliadas individualmente a perda (*loss*) e a acurácia nos dados de validação, conforme apresentado na Figura 18. Entre os modelos avaliados, aquele gerado no fold 2 destacou-se por apresentar simultaneamente a menor perda e a maior acurácia de validação (Tabela 4). Diante desse desempenho superior, o modelo correspondente ao fold 2 foi selecionado para a etapa de predição espacial. A escolha desse modelo implica a utilização de uma rede com melhor capacidade de generalização para os dados não vistos durante o treinamento, conferindo maior confiabilidade aos mapas de predição gerados. Essa decisão assegura que a inferência sobre as áreas de estudo esteja baseada no modelo com melhor desempenho durante o processo de validação cruzada.

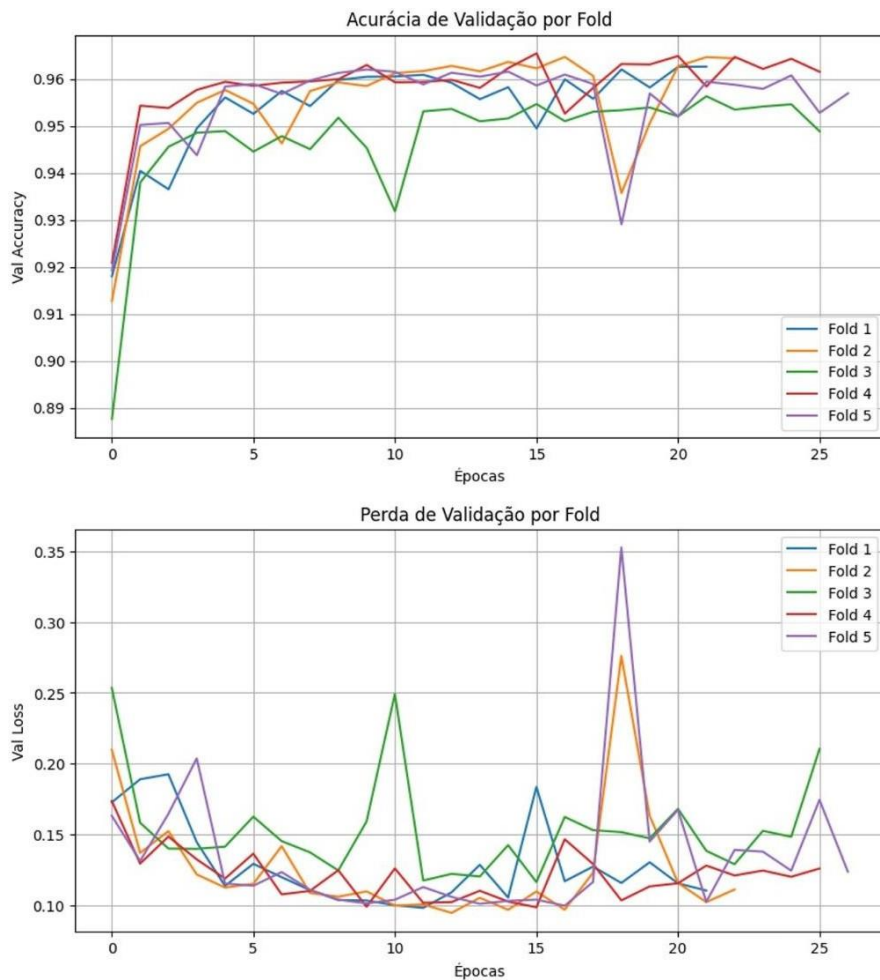


Figura 18 Evolução da acurácia e da perda de validação por época para cada um dos folds durante o treinamento. O gráfico superior mostra a acurácia de validação, enquanto o gráfico inferior apresenta a perda de validação.

Table 4 Valores de perda e acurácia dos dados de validação em cada fold durante o treinamento.

Folds	Perda de validação	Acurácia de validação
1	0.099	0.962
2	0.095	0.965
3	0.117	0.950
4	0.099	0.962
5	0.100	0.957

Além da seleção do modelo com base nos valores de desempenho quantitativo, avaliamos também sua capacidade de segmentação visual, ou seja, a habilidade de distinguir e localizar com precisão a copa da espécie alvo nas imagens. O resultado obtido com o Modelo 2 evidencia o potencial da aplicação de CNNs com arquitetura U-Net para essa tarefa, apresentando alta eficácia na delimitação das copas da espécie invasora *Muntingia calabura*.

Observa-se que as regiões de alta probabilidade de predição coincidem com a morfologia e o padrão espacial característico da espécie, reforçando a confiabilidade do modelo para aplicação em mapeamentos operacionais.

Alguns pontos da segmentação mostraram uma baixa predição (< 0.2) na área central da copa da espécie invasora, indicando que houve certa confusão na classificação nesses pontos (Figura 19). Esse resultado sugere limitações do modelo na identificação desses pontos como componentes do entorno, possivelmente associadas à alta similaridade espectral entre a copa da espécie invasora e a vegetação nativa adjacente, o que reduz a capacidade de distinção pelo algoritmo. Algumas ações podem ser tomadas para aprimoração do modelo, especialmente nas estratégias de segmentação, como o uso de sobreposição entre tiles (sliding windows), além do aumento da diversidade no conjunto de treinamento.

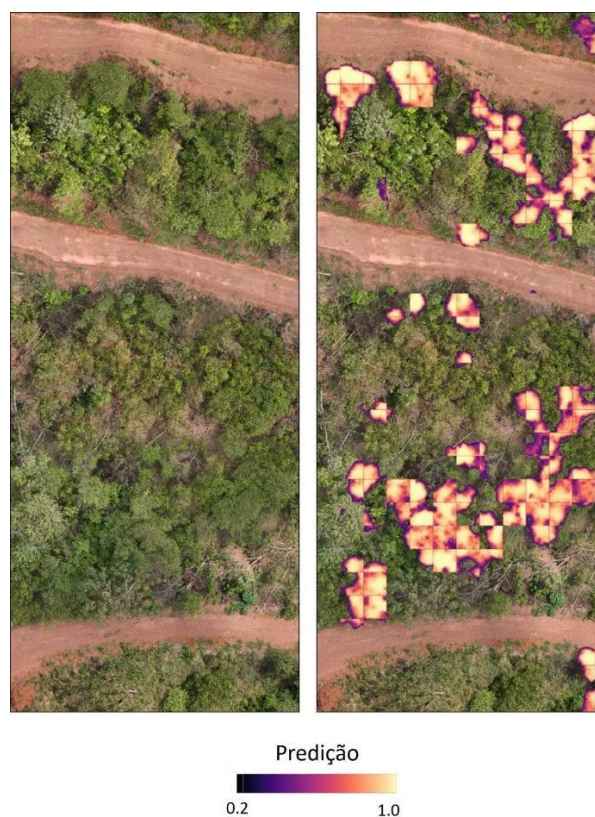


Figura 19 Resultado da segmentação da espécie invasora na área de treinamento. À esquerda, imagem original da área utilizada como base para comparação visual. À direita, mapa de predição gerado pelo modelo, indicando a probabilidade de presença da espécie invasora.

Uma vez que o diagnóstico de treinamento e validação atingiu valores satisfatórios e

que as predições dos subsets demonstraram a capacidade do modelo em delimitar com precisão a espécie invasora, seguimos com a predição para toda a área. Assim, os ortomosaicos das PDEs Sul 4 e Oeste foram submetidos à predição para a identificação da *M. calabura* nas áreas (Figura 20). O modelo gerou mapas de probabilidade de ocorrência da espécie, indicando as regiões com maior predição à presença com base em padrões espectrais e morfológicos.

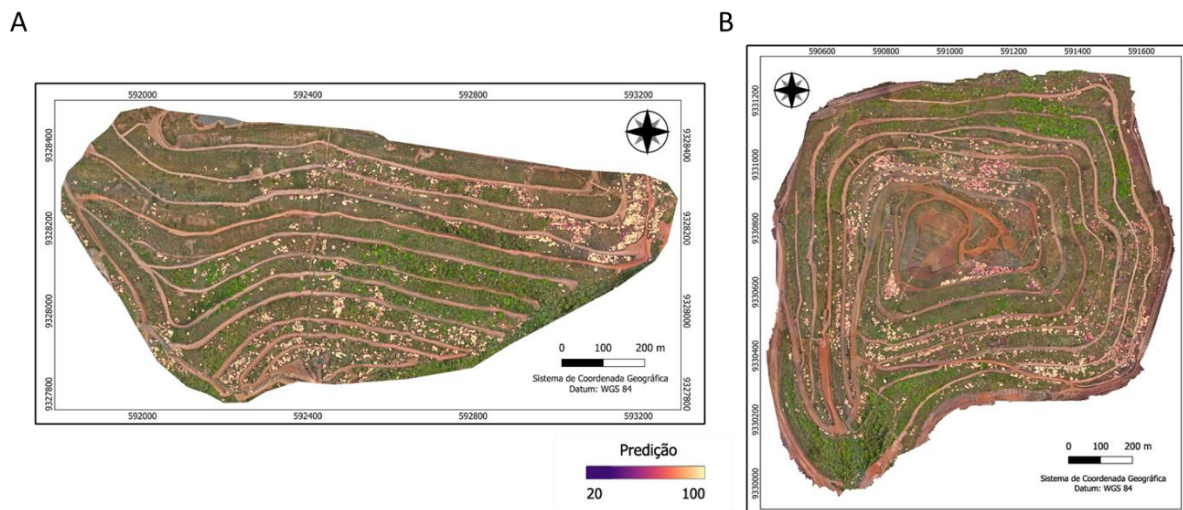


Figura 20 Mapa de 2023 com as predições de ocorrência da espécie invasora *Muntingia calabura* ao longo das pilhas de estéril Sul 4 (A) e Oeste (B), gerado a partir de modelo de segmentação U-Net. A escala de cores representa a probabilidade de presença da espécie invasora, variando de 0,2 a 1,0. A imagem de fundo corresponde aos ortomosaicos.

A matriz de confusão resume os resultados da classificação entre áreas com e sem a presença da espécie invasora, com base em 5.000 pontos aleatoriamente designados em cada uma das pilhas de estéril (Figura 21). Na área de treinamento, 966 correspondem à presença da espécie invasora e 4034 à sua ausência, enquanto na área teste 937 correspondem à presença da espécie invasora e 4063 à sua ausência. Considerando os acertos e erros entre o predito e o real da classe da espécie invasora, os resultados indicam o alto poder de generalização do modelo durante a classificação, onde a maioria das áreas classificadas como espécie invasora de fato correspondem a presença da espécie.

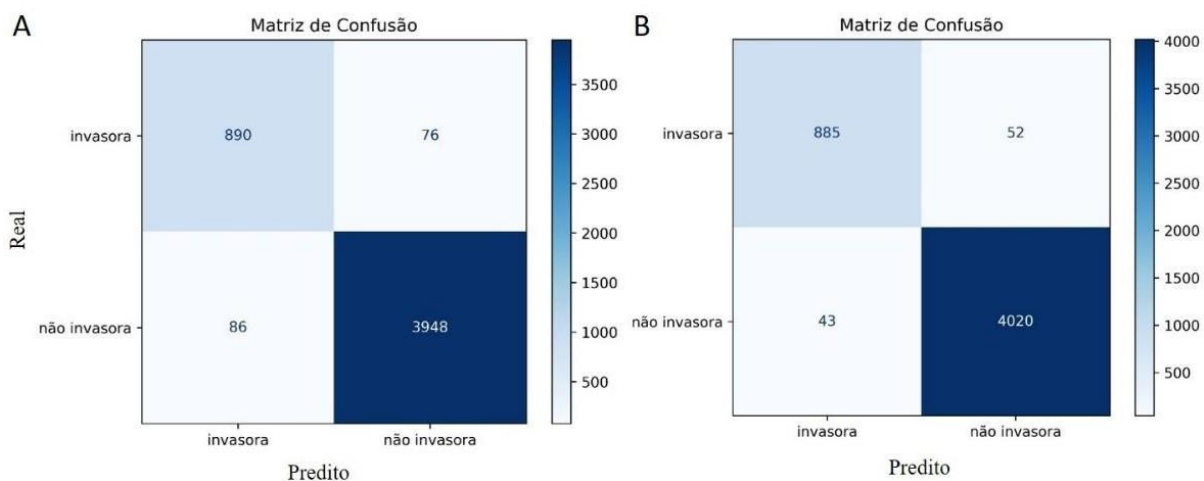


Figura 21 Matriz de confusão criada a partir de dados reais e preditos pela classificação da espécie invasora *Muntingia calabura* nas pilhas de estéril Sul 4 (A) e Oeste (B).

Os resultados da avaliação do modelo apresentaram uma acurácia geral de 97% para as predições da PDE Sul 4 e 98% da PDE Oeste (Tabela 5), resultado similar ao observado durante o treinamento e na validação. Para ambas as áreas, o modelo demonstrou alta capacidade de identificar corretamente as ocorrências reais da invasora, com equilíbrio entre a capacidade de identificar verdadeiros positivos e evitar falsos positivos. Em relação a classe não invasora, o modelo também apresentou alta robustez em distinguir entre presença e ausência da espécie, atingindo até 99% de desempenho nas métricas de precisão, sensibilidade e F1-score. Esses resultados apontam a boa performance de generalização do modelo em áreas de recuperação não treinadas de forma eficiente, permitindo a sua utilização para o monitoramento das áreas de PDE de Carajás.

Tabela 5 Resultado dos índices de Precisão, sensibilidade, F1-score e a acurácia geral da classificação da espécie invasora *Muntingia calabura* nas pilhas de estéril Sul 4 e Oeste.

		Classe	Precisão	Sensibilidade	F1-score	Suporte
PDE	Sul 4	Invasora	0.91	0.92	0.92	966
		Não invasora	0.98	0.98	0.98	4034
		Acurácia geral			0.97	5000
PDE	Oeste	Invasora	0.95	0.94	0.95	937
		Não invasora	0.99	0.99	0.99	4063
		Acurácia geral			0.98	5000

Os resultados detalhados da segmentação mostram que as regiões de alta probabilidade de predição coincidem com a morfologia e o padrão espacial característico da espécie, reforçando a confiabilidade do modelo para aplicação em mapeamentos operacionais. Alguns pontos da segmentação mostraram uma baixa predição (< 0.2) na área central da copa da espécie invasora, indicando que houve certa confusão na classificação nesses pontos (Figura 22). Isso pode estar relacionado à semelhança espectral entre a copa da espécie invasora e a vegetação nativa adjacente, dificultando a distinção nesses pontos pelo modelo. Algumas ações podem ser tomadas para aprimoramento do modelo, especialmente nas estratégias de segmentação, como o uso de sobreposição entre os tiles ou o aumento do número e diversidade no conjunto de treinamento. Ainda assim, o desempenho geral da CNN foi consistente e robusto, com métricas elevadas de acurácia e baixa variabilidade entre os folds, indicando boa generalização e confiabilidade.

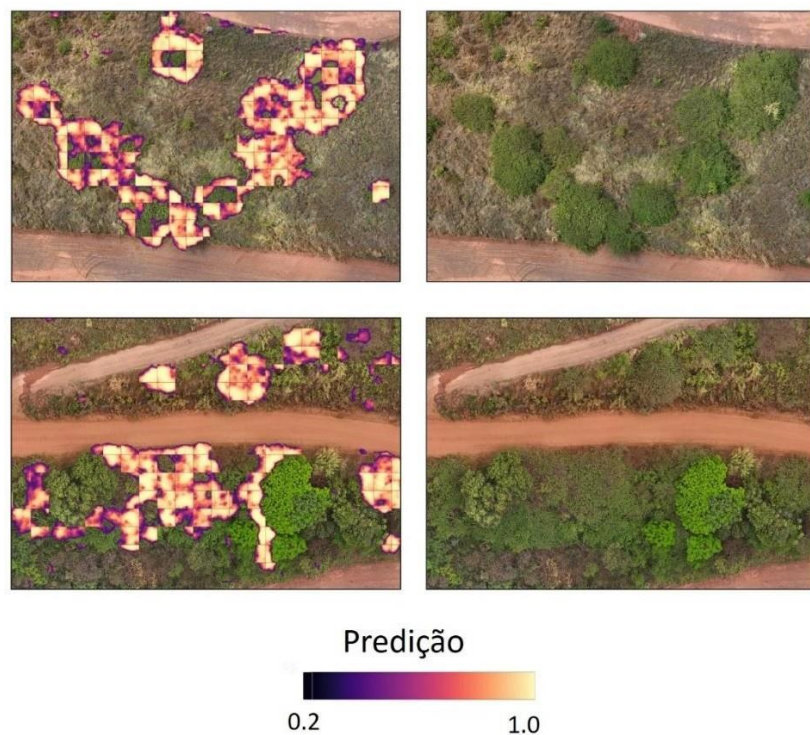


Figura 22 Segmentação da espécie invasora *Muntingia calabura* L. (Muntingiaceae) na PDE Oeste, área teste. Mapa de predição com as probabilidades de presença estimadas pelo modelo e ortofoto original utilizada como entrada para a predição.

5.4 Discussão

Os resultados obtidos ao longo das etapas de treinamento, validação e aplicação do modelo de segmentação baseado em redes neurais convolucionais com arquitetura U-Net demonstram a robustez e a elevada capacidade preditiva da abordagem para o mapeamento da espécie invasora *Muntingia calabura* em áreas de recuperação ambiental na região de Carajás. O modelo selecionado por validação cruzada apresentou desempenho consistentemente elevado, com valores de acurácia, precisão, sensibilidade e F1-score superiores a 97% tanto nos dados de validação quanto na área teste, indicando boa generalização espacial e baixo risco de sobreajuste. Esses resultados evidenciam o potencial de técnicas de aprendizado profundo aplicadas a ortomosaicos de alta resolução para a detecção automatizada de espécies invasoras em ambientes complexos.

A análise espacial das predições revelou padrões recorrentes de ocupação da espécie invasora, caracterizados pela formação de manchas relativamente homogêneas nas pilhas de estéril Sul 4 e Oeste. Em ambas as áreas, *Muntingia calabura* apresentou maior dominância em ambientes com baixa densidade vegetal e cobertura aberta, sendo significativamente menos frequente em trechos com vegetação mais densa e dossel já estabelecido. Embora a espécie apresente menor incidência em áreas com dossel formado, a detecção de manchas isoladas em ambientes vegetados sugere um potencial de avanço mais lento, porém contínuo, o que representa um alerta para a possibilidade de invasão progressiva de áreas naturais adjacentes. A recorrência desses padrões espaciais em diferentes locais indica um comportamento invasivo relativamente previsível, o que pode subsidiar estratégias direcionadas de monitoramento, manejo e controle em áreas de recuperação com características ambientais semelhantes.

Apesar do alto desempenho global, observaram-se erros pontuais de segmentação em regiões com maior complexidade visual, como áreas com sobreposição de copas, variações acentuadas de iluminação e elevada similaridade espectral entre *Muntingia calabura* e espécies nativas. Essas limitações ocorreram principalmente nas bordas das copas e em zonas de transição da vegetação, onde a heterogeneidade estrutural e espectral tende a reduzir a precisão da classificação, além de algumas regiões centrais da copa, possivelmente associadas a efeitos de sombreamento interno ou variações na densidade foliar. Desafios dessa natureza são recorrentes em aplicações de segmentação semântica em ambientes naturais heterogêneos e indicam que aprimoramentos metodológicos, como o uso de janelas deslizantes com maior sobreposição, estratégias mais abrangentes de aumento de dados e a incorporação de informações multiespectrais, podem contribuir para o refinamento do modelo e para a redução

de incertezas locais nas predições.

De forma geral, a consistência dos resultados obtidos em diferentes áreas, aliada à elevada capacidade de generalização do modelo, evidencia o potencial do uso de redes neurais convolucionais, especialmente arquiteturas do tipo U-Net, para o monitoramento em larga escala de espécies invasoras em projetos de recuperação ambiental. A aplicação de técnicas de aprendizado profundo a ortomosaicos de alta resolução mostra-se uma ferramenta promissora de apoio à gestão ambiental, permitindo a identificação precoce de focos de invasão, a priorização de áreas para intervenção e o fortalecimento da tomada de decisão em contextos de elevada complexidade ecológica e vulnerabilidade à invasão biológica. Nesse sentido, a integração entre ferramentas de sensoriamento remoto, inteligência artificial e estratégias de manejo adaptativo pode contribuir significativamente para aumentar a eficácia das ações de monitoramento e controle de espécies invasoras em paisagens em processo recuperação.

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6. CONCLUSÃO GERAL

Este trabalho evidencia que a invasão biológica constitui um dos principais entraves à recuperação de áreas degradadas, particularmente em paisagens mineradas inseridas em mosaicos ecológicos que incluem ecossistemas altamente sensíveis, como as cangas da Floresta Nacional de Carajás. Os resultados obtidos reforçam a necessidade de incorporação do manejo de espécies invasoras como componente estruturante dos protocolos de recuperação, tendo em vista seus efeitos sobre o estabelecimento de espécies nativas, a organização funcional das comunidades e a trajetória sucessional dos sistemas em recuperação.

No que se refere à ecologia de invasão, foi observado que a espécie invasora *Melinis minutiflora* apresenta elevada capacidade de ajuste às condições edáficas características da canga, o que amplia seu potencial de estabelecimento e persistência nesses ambientes. Tal evidência indica que áreas em processo de recuperação podem atuar como focos de propagação, favorecendo o fluxo de propágulos para ecossistemas naturais adjacentes e, conseqüentemente, elevando o risco de invasão secundária. Nesse contexto, o controle direto da espécie invasora aparece como medida indispensável, sobretudo em cenários de baixa resistência biótica. Adicionalmente, os resultados demonstram que intervenções edáficas desempenham papel determinante na mediação das interações competitivas entre espécies nativas e invasoras. A restrição da fertilização nitrogenada, ao favorecer o incremento da cobertura de espécies nativas e limitar o desempenho de invasoras, evidencia que o manejo do solo deve ser concebido como ferramenta estratégica para direcionar trajetórias sucessionais mais favoráveis à recuperação.

No contexto funcional, a invasão por *Muntingia calabura* revelou-se capaz de promover alterações significativas na estrutura funcional das comunidades lenhosas, mesmo em contextos de aparente similaridade funcional com espécies nativas. A manutenção de valores médios de traços funcionais contrasta com a redução da diversidade funcional, a homogeneização das estratégias ecológicas e a reorganização das contribuições relativas das espécies. Esses resultados indicam que abordagens baseadas exclusivamente na composição taxonômica ou em métricas funcionais médias podem superestimar o sucesso da recuperação, ao não capturar perdas associadas à redundância funcional e à resiliência ecológica. Nesse sentido, a identificação de espécies nativas com funções ecológicas-chave emerge como subsídio fundamental para estratégias de enriquecimento, contribuindo para o aumento da estabilidade e da capacidade de resposta dos sistemas recuperados frente a distúrbios.

No âmbito espacial, os modelos preditivos desenvolvidos apresentaram elevada acurácia na identificação da distribuição de *M. calabura*, evidenciando o potencial da modelagem como

ferramenta de suporte à tomada de decisão em programas de recuperação. A identificação de padrões espaciais recorrentes, caracterizados pela formação de manchas homogêneas em determinadas unidades da paisagem, sugere a existência de determinantes ambientais e operacionais que conferem previsibilidade ao processo de invasão. Tal previsibilidade permite o delineamento de estratégias de manejo mais eficientes, com priorização de áreas críticas, otimização da alocação de recursos e implementação de ações preventivas e corretivas em escala de paisagem. A implementação dessa metodologia nas práticas de recuperação significam o ponto inicial para uma mitigação responsável e confiável de espécies invasoras, sendo fundamental e eficiente para o combate efetivo a espécies invasoras.

De forma integrada, os resultados demonstram que o sucesso da recuperação de áreas degradadas está condicionado à articulação entre diferentes dimensões ecológicas e operacionais. O controle de espécies invasoras, o manejo edáfico, a incorporação de abordagens baseadas em traços funcionais e o uso de ferramentas de modelagem espacial constituem ações complementares de um mesmo processo de intervenção, cuja eficácia depende de sua atuação conjunta e coordenada. O manejo edáfico atua na modulação das condições abióticas, influenciando diretamente os filtros ambientais que regulam o estabelecimento das espécies. O controle de invasoras, por sua vez, reduz a pressão competitiva e a entrada contínua de propágulos, criando janelas de oportunidade para o recrutamento de espécies nativas. A incorporação de abordagens funcionais orienta a seleção de espécies capazes de ocupar nichos complementares e desempenhar funções ecológicas-chave, aumentando a redundância e a resiliência do sistema. Por fim, a modelagem espacial permite explicitar a heterogeneidade da paisagem, estimar a distribuição e o tamanho populacional da espécie invasora, avaliar a eficácia das intervenções implementadas e prever áreas de maior suscetibilidade à invasão, subsidiando estratégias de manejo mais eficientes e direcionadas. Assim, tais componentes operam de forma sinérgica na condução de trajetórias sucessionais mais estáveis e menos suscetíveis à reinvasão. Além disso, esses elementos não apenas mitigam os efeitos da invasão biológica, mas também promovem o estabelecimento de comunidades nativas mais diversas, funcionalmente estruturadas e resilientes, favorecendo a consolidação de sistemas autossustentáveis a longo prazo.

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