

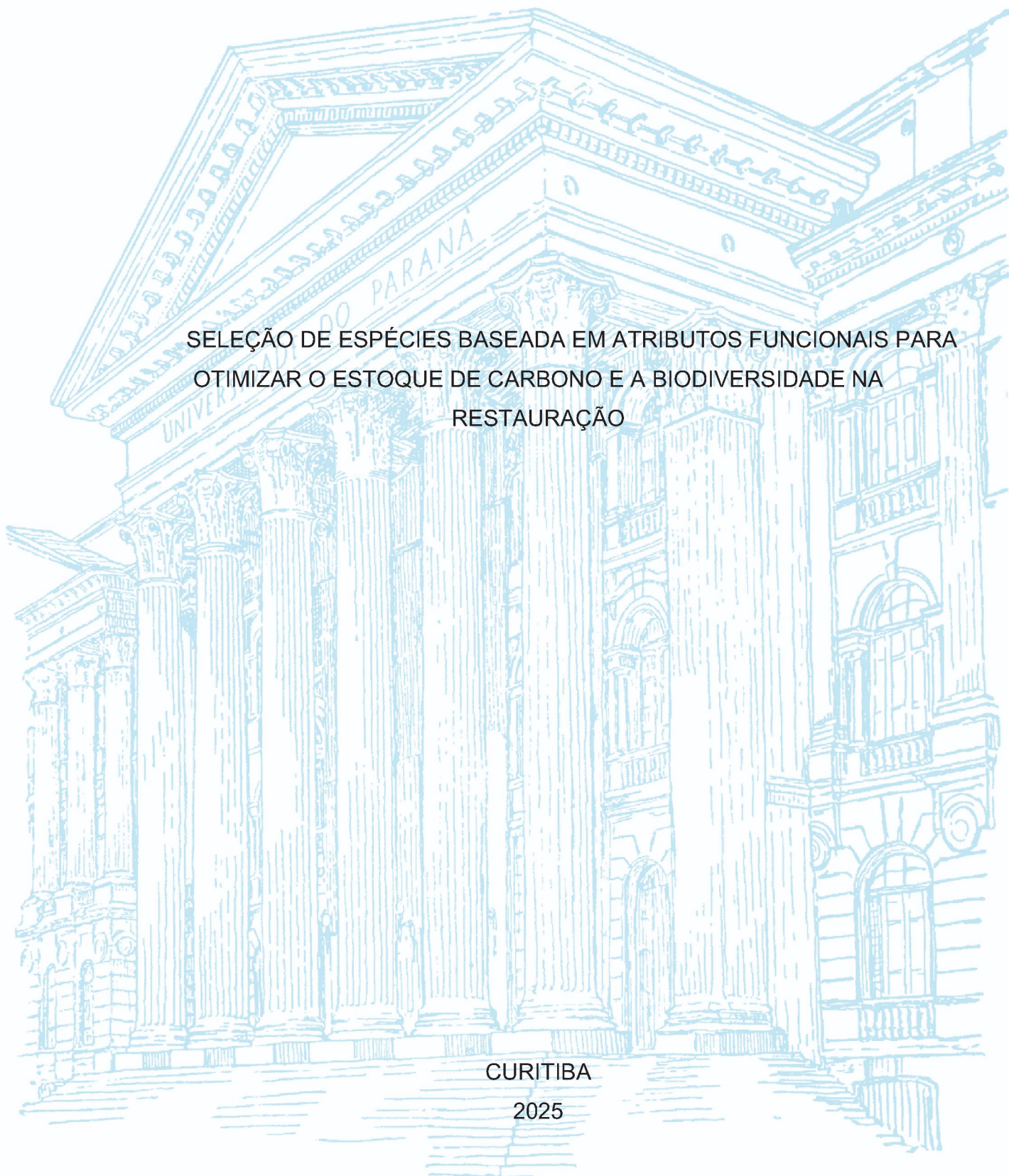
UNIVERSIDADE FEDERAL DO PARANÁ

SUZEL FAEDO PINTO

SELEÇÃO DE ESPÉCIES BASEADA EM ATRIBUTOS FUNCIONAIS PARA
OTIMIZAR O ESTOQUE DE CARBONO E A BIODIVERSIDADE NA
RESTAURAÇÃO

CURITIBA

2025



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RESTAURAÇÃO

Dissertação apresentada ao curso de Pós-Graduação em Ecologia e Conservação, Setor de Ciências Biológicas, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestre em Ecologia e Conservação.

Orientador: Prof.^a Dr. Marcos Bergmann Carlucci.

Coorientador: Prof. Dr. André Ganem Coutinho.

CURITIBA

2025

DADOS INTERNACIONAIS DE CATALOGAÇÃO NA PUBLICAÇÃO (CIP)
UNIVERSIDADE FEDERAL DO PARANÁ
SISTEMA DE BIBLIOTECAS – BIBLIOTECA DE CIÊNCIAS BIOLÓGICAS

Pinto, Suzel Faedo

Seleção de espécies baseada em atributos funcionais para
otimizar o estoque de carbono e a biodiversidade na restauração /
Suzel Faedo Pinto. – Curitiba, 2025.
1 recurso on-line : PDF.

Dissertação (Mestrado) – Universidade Federal do Paraná,
Setor de Ciências Biológicas, Programa de Pós-Graduação em
Ecologia e Conservação.

Orientadora: Prof.º Dr. Marcos Bergmann Carlucci.

Coorientador: Prof. Dr. André Ganem Coutinho.

1. Ecologia de restauração. 2. Florestas tropicais. 3. Sequestro
de carbono. I. Carlucci, Marcos Bergmann, 1985. II. Coutinho,
André Ganem. III. Universidade Federal do Paraná. Setor de
Ciências Biológicas. Programa de Pós-Graduação em Ecologia e
Conservação. IV. Título.

Bibliotecária: Giana Mara Seniski Silva CRB-9/1406



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CONSERVAÇÃO - 40001016048P6

ATA Nº267

ATA DE SESSÃO PÚBLICA DE DEFESA DE MESTRADO PARA A OBTENÇÃO DO GRAU DE MESTRA EM ECOLOGIA E CONSERVAÇÃO

No dia vinte e seis de agosto de dois mil e vinte e cinco às 13:30 horas, na sala 103, auditório da Fisiologia, do setor de Ciências Biológicas, Centro Politécnico- UFPR, foram instaladas as atividades pertinentes ao rito de defesa de dissertação da mestranda **SUZEL FAEDO PINTO**, intitulada: **Seleção de espécies baseada em atributos funcionais para otimizar o estoque de carbono na restauração**, sob orientação do Prof. Dr. MARCOS BERGMANN CARLUCCI. A Banca Examinadora, designada pelo Colegiado do Programa de Pós-Graduação ECOLOGIA E CONSERVAÇÃO da Universidade Federal do Paraná, foi constituída pelos seguintes Membros: MARCOS BERGMANN CARLUCCI (UNIVERSIDADE FEDERAL DO PARANÁ), SANDRA CRISTINA MULLER (UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL), MARCIA CRISTINA MENDES MARQUES (UNIVERSIDADE FEDERAL DO PARANÁ). A presidência iniciou os ritos definidos pelo Colegiado do Programa e, após exarados os pareceres dos membros do comitê examinador e da respectiva contra argumentação, ocorreu a leitura do parecer final da banca examinadora, que decidiu pela APROVAÇÃO. Este resultado deverá ser homologado pelo Colegiado do programa, mediante o atendimento de todas as indicações e correções solicitadas pela banca dentro dos prazos regimentais definidos pelo programa. A outorga de título de mestra está condicionada ao atendimento de todos os requisitos e prazos determinados no regimento do Programa de Pós-Graduação. Nada mais havendo a tratar a presidência deu por encerrada a sessão, da qual eu, MARCOS BERGMANN CARLUCCI, lavrei a presente ata, que vai assinada por mim e pelos demais membros da Comissão Examinadora.

CURITIBA, 26 de Agosto de 2025.

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Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ECOLOGIA E CONSERVAÇÃO da Universidade Federal do Paraná foram convocados para realizar a arguição da dissertação de Mestrado de **SUZEL FAEDO PINTO**, intitulada: **Seleção de espécies baseada em atributos funcionais para otimizar o estoque de carbono na restauração**, sob orientação do Prof. Dr. MARCOS BERGMANN CARLUCCI, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de mestra está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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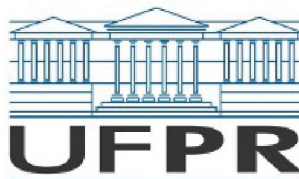
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DECLARAÇÃO

Processo nº 23075.070032/2023-07

O Programa de Pós-Graduação em Ecologia e Conservação da Universidade Federal do Paraná está ciente e de acordo com a solicitação interposta pela Egressa Suzel Faedo Pinto, que defendeu seu mestrado em 26/08/2025. A referida, com anuência de seu orientador prof. Dr. Marcos Bergmann Carlucci, por sugestões dos membros da banca de defesa, solicita a alteração do título de sua dissertação, que passa a ser "SELEÇÃO DE ESPÉCIES BASEADA EM ATRIBUTOS FUNCIONAIS PARA OTIMIZAR O ESTOQUE DE CARBONO E BIODIVERSIDADE NA RESTAURAÇÃO".



Documento assinado eletronicamente por **MARCOS BERGMANN CARLUCCI**,
COORDENADOR(A) DE CURSO DE POS-GRADUACAO (PROGRAMA DE POS-GRADUACAO EM ECOLOGIA E CONSERVACAO) - BL, em 24/10/2025, às 17:19,
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Ao meu filho Luke Faedo Silva. Nosso ipê florido no inverno. *May the forest be with you.*

AGRADECIMENTOS

À família que construí: meu esposo, Arnaldo Junior, e meu filho, Luke, por acreditarem em mim e sonharem esse sonho junto comigo. A Giselle, Rodolfo, Pedro e Lucas por serem família que o Arnaldo me trouxe.

À minha família de origem: minha mãe, Sirlei, meu pai, Adiel, e meus irmãos Suelen, Adiel Junior e Alex, pelo apoio diário, pelas risadas e por estarem presentes mesmo à distância. Às minhas sobrinhas Manoela e Lara por fazerem nossa família completa.

Às amigas e amigos da infância e adolescência de Santa Terezinha de Itaipu, que hoje estão espalhadas pelos mais diversos cantos do mundo e continuam fazendo parte da minha vida; aos amigos da UNICENTRO pela paixão pela biologia e pela conservação, aos amigos da Panelinha, pelos nossos “Cafés com choro” acompanhados de lágrimas, risadas e cuscuz; às amigas da maternidade por dividirem o mesmo neurônio comigo, às amigas da corrida pela companhia e pelo *pace* de fofoca.

Aos meus orientadores, Marcos e André, pela orientação, disponibilidade e paciência. Aos colegas do LABEF, pelo incentivo, colaboração e pelas pausas para cafés, chimarrões e bolos de fubá. Ao PPG-Eco, por me permitir realizar este sonho.

O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de Financiamento 001. Ao CNPq, porque esta dissertação está inserida no projeto “Soluções da Biodiversidade para a Mitigação das Mudanças Climáticas - SoBio-MMC”.

A todos que fizeram parte desse caminho o meu muito obrigada.

"Sou feliz, alegre e forte
Tenho amor e sorte
Aonde quer que eu vá"
(Marisa Monte)

RESUMO

A restauração florestal é reconhecida como uma estratégia essencial para mitigar as mudanças climáticas, promover o sequestro de carbono e recuperar serviços ecossistêmicos. Nesse contexto, a seleção de espécies com base em atributos funcionais tem sido defendida como uma abordagem promissora para potencializar os resultados da restauração ecológica e atender a metas nacionais e internacionais, como o Acordo de Paris, o PLANAVEG e o Pacto pela Restauração da Mata Atlântica. Embora se pressuponha que abordagens orientadas por atributos funcionais, daqui em diante denominadas estrutura metodológica (*framework*), sejam mais eficazes para restaurar ecossistemas com foco na mitigação das mudanças climáticas, ainda é limitado o conhecimento sobre o quanto essas abordagens superam métodos tradicionais, nos quais a escolha das espécies não necessariamente prioriza funções ecológicas específicas. Neste estudo, aplicamos um *framework* recentemente proposto para identificar combinações de espécies de árvores nativas que otimizem múltiplos objetivos da restauração, utilizando como referência dados empíricos *in situ* obtidos em áreas de Floresta Ombrófila Densa no Litoral do Paraná, em regeneração natural há mais de três décadas no âmbito de um programa de conservação pioneiro. Nosso objetivo foi avaliar o potencial dessa abordagem para otimizar a restauração florestal, com foco simultâneo no estoque de carbono e na riqueza de espécies arbóreas. As simulações mostraram que comunidades formadas por espécies funcionalmente complementares podem atingir, em cerca de 40 anos, estoques de carbono equivalentes aos de florestas naturais com mais de 80 anos, antecipando, em décadas, os benefícios climáticos da restauração. Os conjuntos selecionados otimizaram o estoque de carbono, a riqueza de espécies e a variação da densidade da madeira (WD), garantindo a inclusão de espécies iniciais, intermediárias e tardias, estas últimas geralmente associadas a maior WD e elevado potencial de sequestro de carbono. As comparações abrangeram diferentes janelas temporais, permitindo identificar cenários em que o uso do *framework* antecipa, em décadas, a obtenção de estoques de carbono equivalentes aos de florestas maduras. Os resultados reforçam a importância de incorporar abordagens baseadas em atributos funcionais no planejamento da restauração ativa e do enriquecimento florestal, não apenas de espécies de crescimento rápido, mas também de espécies funcionalmente complementares capazes de otimizar serviços ecossistêmicos. Essa abordagem mostra-se promissora para aumentar a eficácia de projetos de restauração ativa em biomas tropicais focados em serviços ecossistêmicos, com potencial de aplicação em larga escala e de integração a políticas públicas de mitigação climática e de conservação da biodiversidade.

Palavras-chave: Atributos funcionais; Florestas tropicais; Restauração ativa; Restauração funcional; Restauração passiva; Seleção de espécies para a restauração; Sequestro de carbono.

ABSTRACT

Forest restoration is recognized as a crucial strategy to mitigate climate change, promote carbon sequestration, and restore ecosystem services. In this context, species selection based on functional attributes has been advocated as a promising approach to enhance the results of ecological restoration and meet national and international goals, such as the Paris Agreement, PLANAVEG, and the Atlantic Forest Restoration Pact. Although it is assumed that approaches guided by functional attributes, hereinafter referred to as a methodological framework, are more effective in restoring ecosystems with a focus on climate change mitigation, knowledge is still limited on how much these approaches outperform traditional methods, in which the choice of species does not necessarily prioritize specific ecological functions. In this study, we applied a recently proposed framework to identify combinations of native tree species that optimize multiple restoration objectives, using as a reference empirical in situ data obtained in areas of Dense Ombrophilous Forest on the coast of Paraná, undergoing natural regeneration for more than three decades within the scope of a pioneering conservation program. Our objective was to evaluate the potential of this approach to optimize forest restoration, with a simultaneous focus on carbon stock and tree species richness. Simulations showed that communities formed by functionally complementary species can reach, in about 40 years, carbon stocks equivalent to those of natural forests over 80 years old, anticipating by decades the climate benefits of restoration. The selected sets optimized carbon stock, species richness, and wood density variation (WD), ensuring the inclusion of early, intermediate, and late-successional species, the latter generally associated with higher WD and high carbon sequestration potential. The comparisons spanned different time windows, enabling the identification of scenarios in which the framework's use anticipates achieving carbon stocks equivalent to those of mature forests by decades. The results reinforce the importance of incorporating approaches based on functional attributes in the planning of active restoration and forest enrichment, including not only fast-growing species but also functionally complementary species that can optimize ecosystem services. This approach holds promise for enhancing the effectiveness of active restoration projects in tropical biomes, focusing on ecosystem services, with potential for large-scale application and integration into public policies aimed at mitigating climate change and conserving biodiversity.

Keywords: Functional attributes; Tropical forests; Active restoration; Functional restoration; Passive restoration; Species selection for restoration; Carbon sequestration.

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LISTA DE ABREVIATURAS OU SIGLAS

AGB – Aboveground Biomass (biomassa acima do solo)

AGR – Annual Growth Rate (taxa de crescimento anual)

BIEN – Botanical Information and Ecology Network

BIOMASS – Pacote R para estimativa de biomassa florestal

D4R – Diversity for Restoration

IAT – Instituto Água e Terra (Paraná)

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

MDS – Non-metric Multidimensional Scaling (Escalonamento Multidimensional Não-Métrico)

MMA – Ministério do Meio Ambiente

MMC – Mitigação das Mudanças Climáticas

PLANAVEG – Plano Nacional de Recuperação da Vegetação Nativa

Q3 – Terceiro quartil (Third Quartile)

SOS Mata Atlântica – Fundação SOS Mata Atlântica

SPVS – Sociedade de Pesquisa em Vida Selvagem e Educação Ambiental

TRY – Global Plant Trait Database

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1 INTRODUÇÃO GERAL

A restauração ecológica tem ganhado reconhecimento global como uma das soluções baseadas na natureza mais eficazes para enfrentar a crise climática, conciliando o sequestro de carbono, a conservação da biodiversidade e a recuperação de serviços ecossistêmicos (IPBES, 2019; Chazdon & Brancalion, 2019). Em regiões tropicais, florestas em regeneração desempenham papel essencial na remoção de CO₂ da atmosfera e na restauração da integridade ecológica. Para maximizar esses cobenefícios, é fundamental adotar abordagens estratégicas de seleção de espécies baseadas em atributos funcionais que influenciam diretamente o desempenho dos ecossistemas (Carlucci *et al.*, 2020; Rosenfield *et al.*, 2023).

A Mata Atlântica é um *hotspot* global de biodiversidade (Myers *et al.*, 2000), com menos de 30% de sua cobertura original remanescente e altos níveis de fragmentação decorrentes da expansão agropecuária (Vancine *et al.*, 2024). O bioma abriga mais de 70% da população brasileira, concentra cerca de 80% do PIB nacional e inclui dezenas de territórios indígenas e comunidades tradicionais (Fundação SOS Mata Atlântica, 2023), o que reforça a urgência de ações de restauração em larga escala (Tambosi *et al.*, 2014; Carlucci *et al.*, 2023). Além de sua relevância socioambiental, a Mata Atlântica representa um modelo estratégico para avaliar o potencial de abordagens de restauração funcional, dado seu alto grau de degradação, a disponibilidade de dados ecológicos de longo prazo (especialmente na Floresta Ombrófila Densa) e a necessidade de conciliar conservação e mitigação climática em paisagens complexas.

Para que metas nacionais e internacionais, como o Acordo de Paris (2015), o PLANAVER (2017) e o Pacto pela Restauração da Mata Atlântica (2009), sejam cumpridas, a restauração florestal precisa incorporar o conhecimento sobre o funcionamento dos ecossistemas desde o planejamento. A chamada restauração funcional considera os atributos funcionais das espécies e sua influência sobre processos ecológicos, como a resistência e a resiliência a distúrbios (Laughlin, 2014; Carlucci *et al.*, 2020). Nessa perspectiva, *frameworks* baseados em atributos funcionais têm sido desenvolvidos para otimizar a seleção de espécies nativas e aprimorar a eficiência ecológica dos projetos de restauração (Fremout *et al.*, 2022; Coutinho *et al.*, 2023). Nas últimas décadas,

tem-se observado o surgimento dos chamados *novel ecosystems*, ecossistemas resultantes de intensas pressões antrópicas e de novas combinações de espécies, frequentemente com funções ecológicas distintas das comunidades originais (Hobbs *et al.*, 2006; Murcia *et al.*, 2014). Esse conceito evidencia que, embora certas combinações de espécies possam atingir altos níveis de funcionamento ecológico, nem todas representam trajetórias desejáveis de restauração, especialmente quando se busca a convergência com ecossistemas de referência. Este estudo avança nesse campo ao aplicar um *framework* baseado em atributos funcionais em um bioma tropical mega diverso, avaliando seu potencial para antecipar o acúmulo de carbono e integrar múltiplos objetivos da restauração, também considerando soluções que não se distanciem muito da composição de espécies típica de florestas nativas.

Neste estudo, aplicamos um *framework* de seleção de espécies para a restauração em áreas de Floresta Ombrófila Densa no Litoral do Paraná, utilizando como referência dados empíricos de regeneração natural acumulados ao longo de mais de três décadas (Ferretti & Britez, 2006; Cardoso *et al.*, 2022). Embora o Litoral do Paraná tenha alto potencial de regeneração natural (Cardoso *et al.*, 2022), escolhemos a região como sistema de estudo por conter dados únicos sobre o monitoramento de áreas em restauração de diferentes idades. Compilamos informações sobre a composição de espécies arbóreas em florestas em restauração e em florestas maduras, bem como dados de densidade da madeira e de taxa de crescimento das espécies, o que nos permitiu obter a taxa de acúmulo de carbono por espécie.

O objetivo deste trabalho foi utilizar um *framework* baseado em atributos funcionais para avaliar se sua aplicação pode otimizar a recuperação de carbono em projetos de restauração florestal. Para isso, foram comparados dados empíricos (*in situ*) de florestas em diferentes estágios de regeneração com simulações (*in silico*) geradas pelo *framework*, que consideraram combinações de espécies nativas com potencial funcional para maximizar simultaneamente o estoque de carbono e a riqueza de espécies.

Os resultados dessa investigação são apresentados a seguir, no artigo redigido em inglês, que descreve a aplicação do *framework* baseado em atributos funcionais e as simulações realizadas para avaliar seu potencial na otimização da restauração florestal.

2 TRAIT-BASED SPECIES SELECTION TO OPTIMIZE CARBON STOCKING AND BIODIVERSITY IN RESTORATION

INTRODUCTION

Ecological restoration with native species plays a crucial role in mitigating climate change, particularly through carbon sequestration and storage (IPBES, 2019; Chazdon & Brancalion, 2019). Regenerating forests offer substantial co-benefits for carbon capture and biodiversity conservation, highlighting the broader relevance of restoration beyond climate goals (Rodrigues *et al.*, 2023). Maximizing these co-benefits requires a functional approach to species selection (Laughlin 2014; Carlucci *et al.*, 2020), tailored to local contexts and objectives (Brancalion *et al.*, 2023). However, implementing effective large-scale restoration strategies continues to face significant challenges, including the appropriate selection of species (Carlucci *et al.* 2020) and the economic feasibility of the adopted approaches (Crouzeilles *et al.*, 2017). This study addresses these challenges by testing the effectiveness of an in-silico species selection framework, comparing its outputs with empirical data from in-situ forest recovery. We simulated the restoration process using different sets of native species from the local species pool, assuming these species could have been used from the outset of restoration interventions. We expect that species selection frameworks enable finding combinations of native species that optimize carbon stock accumulation amid multiple combinations of locally native species available from regional species pools. Optimizing carbon stock over shorter timescales would offer promising insights for more effective and functional restoration planning in support of climate mitigation goals.

Climate regulation is one of the primary ecosystem services (ES), with carbon stocks being a relevant indicator of this process (Millennium Ecosystem Assessment, 2005; IPBES, 2022). To mitigate the climate crisis, we need to restore ecosystems on a large scale (von Holle *et al.*, 2020). Frameworks for species selection based on functional traits have emerged as promising tools to explicitly target ecosystem services since the planning of restoration (reviewed by Carlucci *et al.* 2020). These frameworks focus on identifying species sets for active restoration or enrichment of restoration that optimize specific targeted

ecosystem services (Coutinho *et al.*, 2023; Coutinho, 2023). Trait-based frameworks for species selection are relatively recent in the history of restoration ecology and have emerged as promising tools to support restoration planning (Laughlin, 2014; Laughlin *et al.*, 2018; Fremout *et al.*, 2022; Coutinho *et al.*, 2023; Cianciaruso *et al.*, 2025). These frameworks not only suggest suitable species but also determine their optimal proportions to achieve specific ecosystem services (Carlucci *et al.* 2020). Recent developments enable working with large species pools and comparing their functional composition with that of reference ecosystems (Coutinho *et al.*, 2023) or enriching ongoing restoration by selecting species that will help reach local ecosystem service thresholds (Coutinho *et al.*, 2023). The most recent advancements of this framework enable the selection of species to optimize carbon stocks over time (Coutinho *et al.*, 2023). These frameworks have the potential to improve the provision of ecosystem services in active restoration through optimized species selection. Therefore, evaluating the expected carbon storage derived from in-silico species selection for restoration (Carlucci *et al.*, 2020) provides insights into the potential advantages and constraints of this approach when compared with ongoing in-situ restoration efforts.

Frameworks for species selection are primarily designed to guide active restoration, which involves direct human interventions such as planting nursery-grown saplings or sowing seeds to accelerate ecological succession in degraded landscapes (Chazdon, 2017). While these interventions can be effective in promoting specific outcomes, they are generally more costly and logistically demanding than approaches based on natural regeneration or assisted natural regeneration (Crouzeilles *et al.*, 2017; Strassburg *et al.*, 2020). Nevertheless, active restoration is often recommended in contexts where natural regeneration is unlikely to succeed due to factors such as high rates of land use conversion at the landscape scale or limited seed dispersal, which may prevent recovering communities from achieving high functional or taxonomic diversity (Brancalion *et al.*, 2019).

The present study aimed to test a trait-based framework for species selection to assess whether its application could optimize carbon recovery in forest restoration. To this end, we compared comprehensive in-situ data from ongoing restoration with in-silico simulations generated by the framework. The

study was conducted in the Atlantic Forest hotspot, specifically within the coastal tropical rainforest of Paraná State, southern Brazil, where protected areas were established approximately three decades ago. These include the Guaricica and Águas Private Nature Reserves, both of which had previously been subjected to buffalo farming and selective logging (Ferretti & Britez, 2006). Although the coastal tropical rainforest in Paraná is relatively well-conserved and may recover effectively through natural regeneration, few regions of the Atlantic Forest provide high-quality temporal restoration data comparable to those available for the Paraná coast. We used these data as a reference for carbon stocks by forest age and compared them with estimates produced by the framework, which identifies optimal native species combinations. By contrasting in-situ and in-silico restorations, we sought to identify strategies that enhance carbon stocks and advance functional recovery, not only in Atlantic Forest rainforests but also in other tropical forests worldwide.

METHODS

Study areas

This study was carried out in two private nature reserves: the Guaricica Nature Reserve (8,600 ha; 25°19'S, 45°42'W) and the Águas Nature Reserve (508 ha; 25°21'S, 48°46'W). Both areas are managed by the Society for Wildlife Research and Environmental Education (SPVS) in Antonina, Paraná State, southern Brazil, and are located within the coastal Atlantic rainforest (Figure 1).

Historically, the areas were subject to extensive land use, including buffalo ranching and selective logging, which resulted in significant degradation of the native vegetation. Since their acquisition and protection by the SPVS in the early 2000s, both reserves have undergone passive ecological restoration, primarily through natural regeneration processes. This approach has allowed forest structure and biodiversity to recover gradually over time, particularly due to the proximity to old-growth remnants and the exclusion of recurring disturbances.

Tree community data

The available data come from long-term studies of forests undergoing natural regeneration. The data analyzed in this study were obtained within the scope of

the Solutions of Biodiversity for Climate Change Mitigation (SoBio) project. The first census was conducted in 2010 (Cardoso *et al.*, 2022), the second in 2015 and 2016 (Capellesso, 2020; Cequinel *et al.*, 2018), and the third in 2021 (Alves, 2023). We considered four non-overlapping age classes following abandonment (Capellesso, 2020), as follows: 7 to 17 years (age class 1), 20 to 30 years (age class 2), 35 to 55 years (age class 3), and 80 years or older (age class 4). In all areas, following the removal of buffalo grazing, forest recovery occurred through natural regeneration. In each class, 10 circular plots (14 m in radius) were established, except in plots older than 80 years, where five plots were used, totaling 2.2 ha and 35 plots in total. A total of 289 tree species were identified in the plots.

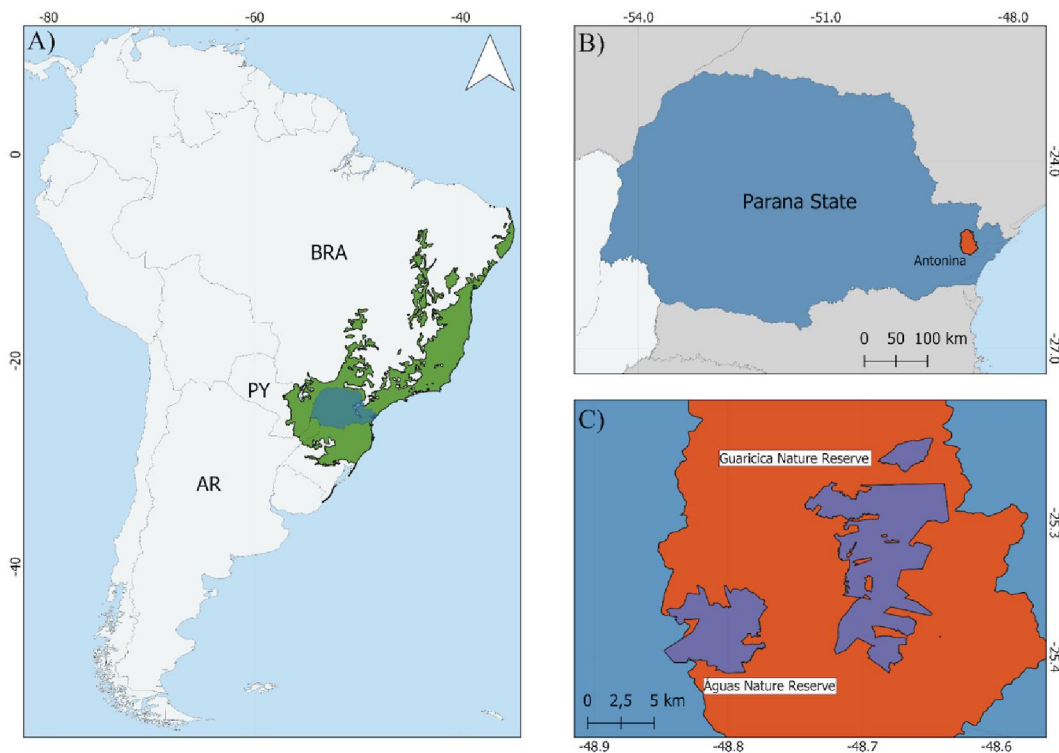


Figura 1: Location of the Guaricica Natural Reserve and the Águas Natural Reserve (C) in Paraná State (B), southern Brazil (A).

Framework of species selection for restoration

We used the framework developed by Coutinho *et al.* (2023), which selects sets of native species from informed species pools to optimize ecosystem services. Using the approach proposed by Debastiani *et al.* (In prep.), we applied an adapted version of this framework to optimize the increase of carbon stocks

over time while seeking solutions that maintain high species richness. The resulting species sets were used to simulate restoration outcomes (*in silico*). We compared their estimated carbon stocks across different temporal windows (80All, 80Ava, 40All, 40Ava) with empirical carbon data from naturally regenerating forest communities in the Guaricica and Águas Natural Reserves, located on the coast of Paraná, Brazil.

Simulated communities were generated based on the combinations of species defined for each scenario, assigning relative abundances to meet the functional diversity and carbon stock criteria previously established. To implement this framework, we compiled functional and empirical data from native tree species of the Atlantic Forest. The functional trait used was wood density (WD; g cm^{-3}), due to its strong relationship with biomass accumulation and successional dynamics. Reference communities corresponded to permanent plots monitored in the Guaricica and Águas Natural Reserves (Antonina, Paraná State, southern Brazil), including forest censuses from 2010 (Cardoso *et al.*, 2022), 2015–2016 (Capellesso *et al.*, 2020), and 2021 (Alves *et al.*, 2023). These datasets represent a chronosequence from 10 to 80 years of natural regeneration, providing empirical bases for the carbon and functional thresholds used in the simulations.

The regional species pool included all species recorded in these reference plots plus those available in SPVS nurseries. Four thresholds guided community selection: two based on the maximum and 75% of the maximum aboveground carbon stock in the 80-year and 40-year reference plots, and a threshold corresponding to the 75th percentile of functional diversity (Rao's Q = 1.02), reflecting successional heterogeneity. Each simulated community contained 1,000 individuals and 20–50 species, distributed according to the abundance structure of reference plots. Simulations were performed using a constrained random assembly approach, generating 10,000 combinations per scenario over a 40-year projection period, with random processes initialized under a fixed seed to ensure reproducibility.

We grouped the simulations into four analytical scenarios, defined by the reference thresholds and the species combinations used: Scenario 80All – threshold derived from plots older than 80 years, using all species from the regional pool; Scenario 80Ava – same threshold, but using only species available

for restoration; Scenario 40All – threshold derived from plots aged 40–50 years, using all species; and Scenario 40Ava – same threshold, but restricted to the available species. In addition, we considered as a comparison set the empirical communities observed in the field (reference plots).

In our context, a species pool refers to the list of native species recorded under a given condition or in a specific study area. A “community,” in turn, refers to the set of species co-occurring within the same sampling unit (in this case, plots), including their composition and relative abundances. Each analytical scenario therefore represents a set of empirical or simulated communities under the same threshold and species availability condition, with carbon accumulation estimated at 40 years — a central value representing the average age class (30–50 years).

The simulations were projected over a 40-year period, corresponding to a realistic time frame for monitoring and crediting cycles in forest carbon projects, which are typically evaluated every 30 years. This temporal horizon captures a critical successional window during which restoration interventions can demonstrate measurable gains in biomass and carbon storage. In addition, many carbon certification programs assign higher market value to projects that combine high native species diversity with verified carbon sequestration, commonly referred to as *biodiversity carbon credits* or *premium restoration labels*. Therefore, the 40-year time frame adopted here reflects both ecological relevance and practical applicability for evaluating restoration performance under current carbon market standards. The richness values used in the communities simulated by the framework ranged from a minimum of 20 to a maximum of 90 species, following recommendations for Atlantic Forest restoration (Brancalion *et al.*, 2019). Considering the ecological importance of zoochoric species in tropical forest ecosystems, we incorporated a minimum threshold of 40 % zoochoric species—those whose seeds are dispersed by animals—in our simulations, as mandated by state environmental regulations (IAT, 2020). In our study, the pool of “available species” was defined as the subset of species that have been historically used in active restoration efforts within the Guaricica and Águas reserves. This decision ensured the simulations were grounded in realistic restoration conditions and aligned with local operational contexts.

We calculated the Rao quadratic entropy index (Botta-Dukát, 2005) as a measure of the dispersion of wood density (Rao_WD) in each simulated community, considering both species abundances and wood density (WD) Euclidean distances. To ensure balanced functional diversity, Rao_WD was optimized so that simulated communities comprised both high- and low-WD tree species, thus preventing an overrepresentation of late-successional species typically characterized by high wood density.

To determine the functional species pool used in the simulations, we compiled species available for active restoration from SPVS nurseries and planting records, totaling 114 native species (81 currently cultivated and 37 historically planted, with four overlapping species). These species were compared with the 190 species modeled by the functional framework. Of these, 12 were both simulated and available for restoration. When combined with the 289 species recorded in natural regeneration plots, the regional species pool comprised 403 species (Table 1).

Category	Description	Quantity
Regional species pool	Available or recorded in field censuses	403
Species available for active restoration	Accessible in SPVS nurseries (current + historical)	114
Species used in simulations	Modeled by the framework	190
Simulated species also available	Species selected by the framework and accessible for planting	12

Table 1: Summary of species groups used in this study. The dataset includes species currently or historically available for active restoration through SPVS nurseries, species modeled by the functional framework, and the total regional pool of species recorded either as available or naturally occurring in the reference forests of the Paraná coastal region.

Carbon stock calculation

Of the 289 tree species recorded in the forest censuses, diameter at breast height (DBH) measurements from at least two sampling periods and wood density (WD) data were available for 261 species. DBH data from at least two sampling periods were necessary to estimate the annual growth rate for each species. These data were obtained through collaborations within the scope of the SoBio project and compiled from multiple sources, including the UFPR Atlantic Forest Traits database (Petisco-Souza *et al.*, 2023), TRY (Kattge *et al.*, 2020), BIEN (Maitner *et al.*, 2018). When multiple WD records were available for a given species, we calculated the mean WD per species.

These data were used to calculate mean annual diameter growth rates based on the change in DBH between the two measurement periods for each species. We then estimated the aboveground biomass (AGB) of these species using the BIOMASS R package (Réjou-Méchain *et al.*, 2017) function for moist tropical forests that does not require tree height as an input but uses geographic coordinates to apply the appropriate Chave *et al.* (2014) equation. This equation incorporates DBH and WD as key predictors. Aboveground biomass values were converted to carbon using a factor of 0.456, as proposed by Martin *et al.* (2018). This conversion factor represents the mean carbon fraction in the dry biomass of tropical trees, estimated from empirical measurements encompassing a wide range of species and biogeographic regions.

Calculation of growth curves

The mean growth curve for each species was generated from empirical data, specifically the mean annual growth rate (AGR) of stem diameter obtained from forest monitoring plots. Simulated communities were structured according to species relative abundances using functions from the Resbiota R package (Debastiani *et al.*, in prep.), designed to prevent the overrepresentation of rare species in simulated assemblages. The framework operates at the species level, not the individual level, and does not directly compute carbon accumulation.

To estimate carbon for the simulated communities at 40 years, we used the species-specific growth curves as input in the model, combining them according to the relative abundances defined by the framework. In this manner, the individual species curves were aggregated, weighted by the abundance of each

species in the simulated community, yielding carbon accumulation curves for each simulated community. The 40-year-old simulated communities were generated as projections from species combinations and their growth parameters, rather than representing a subset of the empirical plots within the 35–55-year age class.

To assess the potential for carbon accumulation under different benchmarks, two reference thresholds were defined. For both the 80All/80Ava and 40All/40Ava scenarios, the upper threshold corresponded to the maximum carbon value observed in the field, while the lower threshold was set as the third quartile (Q3) of those values.

RESULTS

Simulated communities containing only available species (black circles) exhibited carbon stock values ranging from approximately 50 to 150 Mg C/ha, within a total possible range of 0 to 250 Mg C/ha. These communities also displayed a wide variation in successional class diversity (Fig. 2). In contrast, simulations including unavailable species (grey points) showed a broader distribution, with several communities surpassing the 80-year carbon thresholds. Reference communities (blue symbols) also presented variation in carbon values, with one 80-year community reaching almost 200 Mg C/ha, highlighting the natural heterogeneity of mature forest stands. Notably, a cluster of simulations using all species (light red shapes) achieved carbon values above the 80-year lower threshold.

The ten most frequent species in each scenario are shown in Table 2. Some species, such as *Jacaranda puberula*, *Vochysia bifalcata*, and *Pera glabrata*, appeared consistently across simulations, indicating their strong contribution to functional complementarity and carbon optimization. These species are pioneers or early secondary species with high growth rates and moderate wood density, favoring rapid canopy closure and carbon accumulation.

When using the 80-year-old plots as the reference threshold, simulations from Scenario 80All (threshold from 80-year-old plots, using all species from the regional pool) produced communities with high carbon accumulation at 40 years. Furthermore, such arrangements have shown the capacity to accumulate, in

around 20 years, carbon values close to those of 40-year-old forests, significantly anticipating climate benefits. Among these, both communities formed by species not available for restoration (Fig. 2, light red dots) and those composed exclusively of available species (Scenario 80Ava – same threshold, but using only species available in local nurseries; Fig. 2, dark red dots) showed promising potential for optimizing carbon stock within the constraints of species availability. In Scenario 80All, although the selected simulations are slightly below the maximum carbon value observed in the 80-year plots, they show a clear pattern of temporal optimization, achieving carbon stocks equivalent to 80 years in just 40 years (Fig. 2). When restricting simulations to available species only (Scenario 80Ava), the efficiency of this optimization is reduced, but not substantially, and still reaches carbon levels comparable to those of 80-year-old forests.

Simulations using the 40-year constraint (orange shapes) tended to concentrate around the 40-year carbon benchmark. In Scenario 40All, the optimization capacity was limited, given that the variation in carbon stocks in this age range is relatively small (Fig. 2). The result considering only available species (Scenario 40Ava) generated similar outputs. Estimated carbon stocks of both scenarios were similar to the reference sites of the same age, resulting in a modest estimated increase in carbon accumulation in comparison to in-situ data.

All simulations represented 40-year projections, where each point corresponds to a simulated community of 1,000 individuals.

The comparison of species composition between in-silico and in-situ restoration revealed distinct patterns in the distribution of community compositions among the simulation scenarios and the reference sites (Figure 2 C). Simulations from the Scenario 80All (light red dots) formed a separate cluster in the upper-right quadrant of the ordination space, indicating high dissimilarity compared to the other groups. In contrast, simulations from Scenario 40All (light orange) showed a broader spread, with many points overlapping with the reference communities (blue symbols), suggesting compositional similarity and a wide range of possible species combinations.

Simulations using only available species in both scenarios (dark orange and dark red) formed tighter clusters with less internal dispersion. Still, they remained distant from the reference communities, indicating lower similarity and reduced variability in species composition.

Overall, the ordination shows a compositional gradient of age of the reference plots along the MDS 1 axis, increasing age from the right to the left. Simulations of Scenario 40All yielded the highest internal variability, suggesting a broader range of compositional outcomes, biased towards older forests. Conversely, simulations constrained to available species resulted in lower variability and higher compositional similarity to younger forests. Species composition of Scenario 80All simulations were more related to older forests, but were the communities more different, in terms of composition, from reference plots. Only the light orange group (Scenario 40All) showed substantial compositional overlap with reference communities, indicating that this configuration better reproduces naturally occurring assemblages.

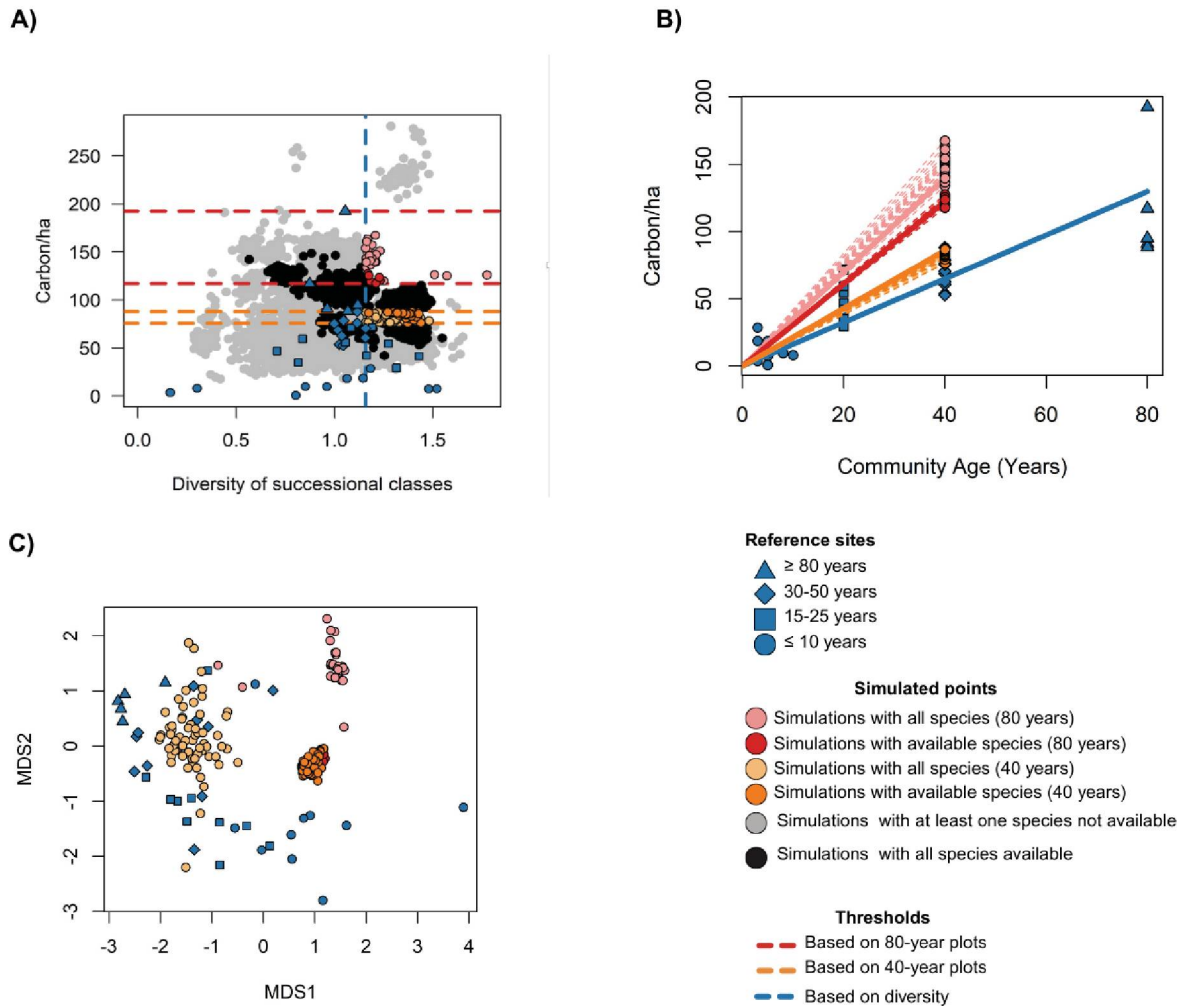


Figure 2: Carbon accumulation (Mg C/ha) as a function of the diversity of successional classes in simulated communities. Blue symbols represent empirical communities from the reference sites: triangles (≥ 80 years), diamonds (30–50 years), squares (15–25 years), and circles (≤ 10 years). Each colored circle represents a simulated community of 1 hectare and 1,000 individuals. Scenario 80All – simulations with all species from the regional pool, threshold based on ≥ 80 -year plots (light red circles). Scenario 80Ava – simulations with only species available in local nurseries, threshold based on ≥ 80 -year plots (dark red circles). Scenario 40All – simulations with all species from the regional pool, threshold based on 40–50-year plots (light orange circles). Scenario 40Ava – simulations with only species available in local nurseries, threshold based on 40–50-year plots (dark orange circles). Grey points indicate simulations with at least one unavailable species. Black points indicate simulations with all species available. Horizontal dashed lines indicate carbon thresholds: upper red = 197.8 Mg C/ha (maximum observed in ≥ 80 -year plots), lower red = 122.6 Mg C/ha (3rd quartile of ≥ 80 -year plots), upper orange = 94.3 Mg C/ha (maximum observed in 40–50-year plots), and lower orange = 78.5 Mg C/ha (3rd quartile of 40–50-year plots). The vertical blue dashed line represents the functional diversity (Rao) threshold of 1.02, corresponding to the 3rd quartile, considering all plots in the database.

40AII	80AII	40Ava	80Ava
<i>Pera glabrata</i>	<i>Jacaranda puberula</i>	<i>Pera glabrata</i>	<i>Jacaranda puberula</i>
<i>Jacaranda puberula</i>	<i>Vochysia bifalcata</i>	<i>Jacaranda puberula</i>	<i>Vochysia bifalcata</i>
<i>Mimosa bimucronata</i>	<i>Psidium cattleianum</i>	<i>Mimosa bimucronata</i>	<i>Alchornea glandulosa</i>
<i>Vochysia bifalcata</i>	<i>Sapium glandulosum</i>	<i>Vochysia bifalcata</i>	<i>Guapira opposita</i>
<i>Guapira opposita</i>	<i>Cecropia glaziovii</i>	<i>Guapira opposita</i>	<i>Inga edulis</i>
<i>Euterpe edulis</i>	<i>Annona dolabripetala</i>	<i>Inga edulis</i>	<i>Bathysa australis</i>
<i>Alchornea glandulosa</i>	<i>Alchornea glandulosa</i>	<i>Alchornea glandulosa</i>	<i>Syagrus romanzoffiana</i>
<i>Inga edulis</i>	<i>Guapira opposita</i>	<i>Nectandra oppositifolia</i>	<i>Nectandra oppositifolia</i>
<i>Nectandra oppositifolia</i>	<i>Cedrela fissilis</i>	<i>Bathysa australis</i>	<i>Alchornea triplinervia</i>
<i>Casearia obliqua</i>	<i>Ocotea catharinensis</i>	<i>Syagrus romanzoffiana</i>	<i>Casearia sylvestris</i>

Table 2: Ten most frequent species in each simulation scenario.

Among the 191 species modeled by the framework, 12 were also available for active restoration (i.e., cultivated in SPVS nurseries or historically planted). These species *Alchornea glandulosa*, *Bathysa australis*, *Casearia sylvestris*, *Cedrela fissilis*, *Guapira opposita*, *Inga edulis*, *Jacaranda puberula*, *Nectandra oppositifolia*, *Pera glabrata*, *Sapium glandulosum*, *Syagrus romanzoffiana*, and *Vochysia bifalcata* represent the intersection between functional optimization outputs and actual species availability, highlighting candidates that combine ecological performance with practical feasibility for restoration.

DISCUSSION

The results indicate that the strategic selection of species based on functional traits can significantly accelerate carbon accumulation in forest restoration projects. In our study, communities selected using a trait-based framework reached aboveground carbon stocks in approximately 40 years equivalent to those of 80-year-old reference forests. Although some simulated communities exceeded the upper carbon threshold observed in 80-year-old reference forests, these configurations were not selected as optimal solutions. Such combinations, while functionally efficient, may represent *novel ecosystems*

— ecological assemblages with species compositions and functional structures that do not occur naturally (Hobbs *et al.*, 2006; Murcia *et al.*, 2014). In the context of restoration, generating novel ecosystems could compromise ecological integrity and reference convergence, diverging from the principles of resilience and self-sustainability that guide ecological restoration (Brancalion & Chazdon, 2017).

The overlap between simulated and available species highlights the potential to translate the theoretical outputs of the framework into practical restoration strategies. The twelve species identified as both functionally optimized and currently available for active restoration (*Alchornea glandulosa*, *Bathysa australis*, *Casearia sylvestris*, *Cedrela fissilis*, *Guapira opposita*, *Inga edulis*, *Jacaranda puberula*, *Nectandra oppositifolia*, *Pera glabrata*, *Sapium glandulosum*, *Syagrus romanzoffiana*, and *Vochysia bifalcata*) combine relevant functional attributes — encompassing a wide range of wood densities, growth rates, and successional stages.

From a restoration planning perspective, the results demonstrate that the trait-based framework can generate species arrangements that are both ecologically efficient and operationally feasible, considering the species already cultivated in local nurseries. This convergence between ecological optimization and practical availability reinforces the potential of the framework as a decision-support tool for restoration projects aimed at climate mitigation. Despite this partial overlap, most of the functionally optimized species are not yet cultivated in nurseries. This absence can be explained by several factors, including the scarcity of reproductive matrices, difficulties in seed collection, and the predominance of pioneer and generalist species in seedling production. Many of these non-available species are naturally rare due to historical selective logging (e.g., *Cedrela fissilis*, *Jacaranda puberula*), anthropogenic pressure, deforestation, and land-use changes (Brancalion *et al.*, 2012). Even among the twelve species shared between simulated and available pools, some — such as *Bathysa australis* and *Nectandra oppositifolia* are relatively uncommon and present challenges for propagation (Brancalion *et al.*, 2012, Brancalion *et al.*, 2018). Therefore, the results not only identify priority species sets for maximizing carbon accumulation but also reveal gaps in the restoration supply chain. Expanding nursery production to include rare or late-successional species would

enable greater functional complementarity, increased carbon storage potential, and restoration trajectories that more closely converge with reference forest communities.

The findings of this study also have direct implications for restoration policies and carbon market standards. Current certification systems — such as voluntary carbon markets and emerging biodiversity credits — increasingly value projects that integrate high native species diversity and measurable ecological co-benefits. Frameworks such as the one applied here can guide the design of “high-value restoration projects,” in which the functional diversity of planted communities translates into superior carbon performance and additional ecosystem services. Furthermore, the 40-year projection period adopted in the simulations aligns with the standard monitoring intervals for carbon credit validation (typically 30–40 years), reinforcing the practical relevance of the framework for operational planning and verification under climate mitigation schemes.

Our selection favored communities that optimized carbon accumulation while remaining ecologically plausible within the natural range of variation of Atlantic Forest reference sites. Achieving this 80-year benchmark in just four decades is remarkable and demonstrates how functional composition, combining fast-growing pioneer and secondary species, can enhance carbon sequestration efficiency. Furthermore, such arrangements have shown the capacity to accumulate carbon values comparable to those of 40-year-old forests, significantly anticipating climate benefits. Large-stature, dense-wood trees typical of late successional stages have greater storage potential due to their size, wood density, and longevity, and some of them may have relatively fast growth rates (Sugiyama *et al.* 2024). Their inclusion in restoration plantings can promote taller canopies and greater woody biomass, accelerating the attainment of mature forest carbon stocks (Sugiyama *et al.* 2024). Brancalion *et al.* (2018) show that the underrepresentation of large, animal-dispersed, large-seeded trees in Atlantic Forest restoration projects reduced projected carbon by 2.8% to 10.6% compared to more functionally diverse plantings. These authors argue that including such missing functional groups is essential to maximize carbon sequestration and ecosystem services in restorations. Functional complementarity — largely driven by differences in wood density among species — emerged as the key mechanism

underlying the higher carbon accumulation observed in optimized communities. This pattern supports the notion that greater functional diversity enhances ecosystem functioning and biomass storage.

At the same time, our findings highlight the importance of balancing taxonomic similarity to reference areas with the optimization of carbon accumulation. We found that scenarios that included only available species, for both 40- and 80-year benchmarks, were restricted in terms of species composition and were more similar to younger forests. This finding indicates that considering only available species biases restoration towards pioneer and more common species, which may homogenize restored forests (Holl *et al.*, 2022). When considering all species from the regional pool, species composition moved closer to older forests, maintaining high variability for the 40-year benchmark, while lower variability and more distinct composition for the 80-year benchmark. Higher similarity to older forests may be explained by the selection of late successional species not available for restoration. In the case of Scenario 80All, likely, more species from forests aging at least 80 years are not available for restoration.

The solutions that optimized carbon stocks tended to exhibit greater diversity of successional classes, combining pioneers, intermediate- and late-successional species (informed by Rao of wood density). This combination is probably underlain by high functional diversity, integrating rapid canopy closure with large-stature, dense-wood, long-lived species that sustain biomass over decades. In contrast, the scenarios restricted to the available species (40Ava and 80Ava) were more similar to intermediate secondary forests, exhibiting carbon values typical of the 40-year old forests, without progressing to the higher levels characteristic of more mature forests. This pattern echoes previous findings showing that pioneer and common secondary species—often small-seeded, wind-dispersed, and fast-growing—are widely used in restoration because they are abundant in nurseries and easy to establish (Holl, 2017; Brancalion *et al.*, 2018). Although solutions based solely on currently available species are effective in establishing forest cover and resemble naturally regenerating forests at equivalent successional stages, they tend to result in more homogeneous compositions with lower functional diversity. This pattern highlights the importance of enriching nurseries with late-successional species, whose

inclusion is essential to enhance functional diversity and ensure restoration trajectories more closely aligned with mature forests (Holl *et al.*, 2022). Studies in the Atlantic Forest show that the predominance of a few hardy, small-seeded species results in plantings more similar to each other than to the diverse reference forests they aim to emulate (Almeida *et al.*, 2024; Almeida *et al.*, 2025). Although this approach is practical and low-risk, it can stall succession in an intermediate state, with carbon stocks plateauing and many late-successional traits underrepresented.

A central implication of our findings is the need to balance effectiveness (rapid carbon gains) with biodiversity and ecological similarity to reference ecosystems. The rapid carbon accumulation observed in simulated communities can be valuable for climate change mitigation, given the carbon sink potential of forest restoration (Brancalion *et al.*, 2019; Crouzeilles *et al.*, 2020). However, an exclusive focus on carbon can oversimplify ecosystem restoration. Recent studies show that carbon stocks and biodiversity do not always correlate. In the subtropical Atlantic Forest, Capellesso *et al.* (2022) found no significant relationship between tree diversity (taxonomic, functional, or phylogenetic) and net carbon sequestration rates across multiple plots. Thus, simply maximizing species richness does not guarantee greater carbon gains. Our simulations indicate that the specific combination of functional traits and species abundance—rather than species diversity per se—drives carbon outcomes. From a management perspective, this implies setting complementary targets for carbon and biodiversity and designing interventions to meet both. Beyond carbon sequestration, trait-optimized communities may also enhance the provision of other ecosystem services, including microclimatic regulation, soil and water retention, and the support of pollinators and seed dispersers (Díaz *et al.*, 2018). Such co-benefits highlight the multifunctional potential of functional restoration approaches. One approach is to combine fast-growing, high-biomass species with a core of native species that maintain the identity of the reference ecosystem and support local fauna (Chazdon *et al.*, 2017; Brancalion *et al.*, 2018). Even better if selected native species can grow relatively fast contributing to faster removal of carbon from the atmosphere (Sugiyama *et al.* 2024), thereby contributing disproportionately to climate mitigation, as it is possible to achieve by applying the framework we used.

In favorable contexts, natural regeneration can provide co-benefits for carbon and biodiversity. For instance, in naturally regenerating areas of the Paraná State rainforests, in the southern Atlantic Forest, species diversity and aboveground carbon have steadily increased with forest age, approaching mature forest values in both metrics (Capellesso *et al.*, 2021). Where landscapes retain resilience (seed banks, nearby remnants, etc.) like in Paraná rainforests, assisted natural regeneration should be prioritized (Cardoso *et al.* 2022), as it is more cost-effective and can achieve high structural complexity and diversity over time (Crouzeilles *et al.*, 2017; Crouzeilles *et al.*, 2020). Conversely, in highly degraded sites or where rapid atmospheric carbon removal is a priority, active restoration interventions since the beginning of restoration with trait-selected species—including those absent from the seed rain—may be necessary to accelerate restoration goals, such as carbon accumulation and the introduction of functional traits that would otherwise take decades to establish (Liebsch *et al.* 2008; Shimamoto *et al.*, 2014; Holl & Aide, 2011). Our results indicate that, although restoration through assisted natural regeneration is successful in Paraná rainforests (Cardoso *et al.* 2022), it is possible to optimize carbon gain in restoration of these forests by including late-successional species with relatively fast growth rates.

All our simulated communities selected species that are native to the study region; however, some combinations, although composed solely of native species, do not naturally co-occur, which may raise uncertainties about their long-term ecological performance. This simulation approach represents a methodological advance for restoration ecology, as it enables testing species combinations and functional hypotheses *in silico* before field implementation, reducing uncertainty and costs during the planning phase. While trait-based frameworks of species selection for restoration promise to improve the recovery of ecosystem services in degraded ecosystems (Laughlin 2014; Carlucci *et al.* 2020; Coutinho *et al.* 2023), it is fundamental that such frameworks are tested experimentally once they are applied in actual restoration (Funk *et al.* 2024). The framework tested here can serve as a practical tool to support restoration planning, helping to identify and prioritize native species combinations that maximize ecosystem functioning under different constraints. Its application can

also guide nursery production and species selection for more efficient and goal-oriented planting designs.

Overall, the trait-based framework demonstrated promising potential to predict carbon optimization patterns in restoration simulations and to inform restoration planning of a tropical ecosystem. Further empirical validation under field conditions will be essential to confirm its applicability and refine its use in practical contexts. By linking functional ecology to restoration practice, trait-based approaches make it possible to optimize the time needed for carbon accumulation while generating co-benefits, including enhanced species diversity and ecosystem resilience.

In the context of the Anthropocene, restoration science faces the dual challenge of mitigating climate change and re-establishing self-sustaining ecosystems. Trait-based frameworks offer a promising path to reconcile these goals by enabling the design of ecologically realistic communities that balance carbon optimization with biodiversity conservation (Chazdon *et al.*, 2021; Holl & Brancalion, 2020). The results presented here contribute to this emerging perspective by demonstrating how functional planning can generate restoration trajectories that are both effective and ecologically coherent.

Finally, we emphasized that the methods employed in this study are replicable and scalable to other tropical contexts, provided that minimally structured regional data are available. In a climate emergency scenario, the adoption of functional trait-based approaches offers a concrete opportunity to accelerate carbon accumulation in ecological restoration projects, promoting nature-based solutions with high impact and practical feasibility. Thus, our research provides relevant insights for the strategic planning of restoration actions aimed at climate change mitigation, with potential for application across different scales and tropical biomes worldwide.

3 CONSIDERAÇÕES FINAIS

Os resultados obtidos neste estudo evidenciam que a simulação de cenários de restauração gerados por um *framework* de seleção de espécies baseado em atributos funcionais relacionados à taxa de acúmulo de carbono constitui uma estratégia eficaz para otimizar o potencial de estoque de carbono em projetos de restauração florestal. As florestas naturais com mais de 80 anos foram utilizadas como referência para a definição do limiar superior de carbono, representando o valor máximo observado nas áreas de Floresta Ombrófila Densa da região estudada — um patamar raramente atingido em iniciativas de restauração. As simulações demonstraram que comunidades formadas por espécies funcionalmente complementares foram capazes de, em aproximadamente 40 anos, atingir níveis de carbono semelhantes a esse limiar. Além disso, essas comunidades acumularam, em cerca de 20 anos, valores de carbono comparáveis aos observados em florestas naturais com 40 anos de regeneração, evidenciando um expressivo potencial de antecipação dos benefícios climáticos promovidos pela restauração ativa orientada por atributos funcionais.

Embora a pesquisa tenha sido conduzida em áreas de Floresta Ombrófila Densa com histórico consolidado de conservação e monitoramento, o *framework* testado neste trabalho apresenta alto potencial de aplicação prática e adaptação a outras fitofisionomias da Mata Atlântica que demandam maior grau de intervenção, como a Floresta Ombrófila Mista e a Floresta Estacional. Nessas regiões, onde a oferta de espécies nativas é mais limitada, a seleção orientada por atributos funcionais pode representar uma estratégia viável para conciliar metas ecológicas e climáticas.

Além da eficiência temporal observada, a abordagem adotada permite integrar múltiplos objetivos da restauração ecológica, como o aumento da diversidade funcional e a convergência com comunidades de referência. No entanto, os resultados também revelaram a existência de *trade-offs*: arranjos mais eficazes em termos de sequestro de carbono podem se distanciar da composição florística típica de florestas regeneradas naturalmente. Esse cenário reforça a importância de decisões integradas que considerem simultaneamente

metas de mitigação climática, conservação da biodiversidade e aspectos sociais e culturais dos territórios restaurados.

Apesar dos avanços metodológicos proporcionados pelos frameworks funcionais, sua aplicação em escala operacional ainda apresenta desafios significativos. Entre os principais obstáculos, destaca-se a dificuldade enfrentada por profissionais da restauração na utilização de grandes volumes de dados ecológicos — como bancos de atributos funcionais e comunidades de referência — cujo processamento exige conhecimentos técnicos em estatística, modelagem e programação. Essa lacuna entre o conhecimento científico e a prática de campo reforça a necessidade de desenvolvimento de ferramentas acessíveis, transparentes e adaptadas à realidade dos projetos, especialmente em contextos com baixa capacidade técnica e limitada diversidade de espécies disponíveis.

Apesar da sobreposição entre espécies simuladas e disponíveis, grande parte das espécies funcionalmente otimizadas ainda não é cultivada nos viveiros. Essa ausência pode ser explicada por diversos fatores, como a escassez de matrizes reprodutivas, a dificuldade de coleta de sementes e a predominância de espécies pioneiras e generalistas na produção de mudas. Muitas dessas espécies ausentes podem ser naturalmente raras devido à extração seletiva de madeira (ex.: *Cedrela fissilis*, *Jacaranda puberula*), à pressão antrópica, ao desmatamento e às mudanças de uso da terra. Mesmo entre as doze espécies que ocorrem simultaneamente nos dois grupos, algumas — como *Bathysia australis*, *Nectandra oppositifolia* e *Vochysia bifalcata* — são pouco comuns e apresentam desafios para a propagação.

Assim, os resultados não apenas indicam grupos funcionais prioritários para maximizar o acúmulo de carbono, mas também evidenciam lacunas na cadeia de suprimento de espécies para restauração. A ampliação da produção de mudas, incluindo espécies raras ou tardias, permitiria maior complementaridade funcional, maior potencial de estoque de carbono e uma trajetória de restauração mais próxima das florestas de referência.

Os resultados deste estudo também têm implicações diretas para políticas públicas de restauração e para os padrões do mercado de créditos de carbono. Sistemas de certificação atuais — como os mercados voluntários de carbono e os créditos de biodiversidade — valorizam cada vez mais projetos que integrem

alta diversidade de espécies nativas e benefícios ecológicos mensuráveis. *Frameworks* como o aplicado neste trabalho podem subsidiar o planejamento de “projetos de restauração de alto valor”, nos quais a diversidade funcional das comunidades plantadas se traduz em melhor desempenho de carbono e em serviços ecossistêmicos adicionais. Além disso, o período de projeção de 40 anos adotado nas simulações coincide com os intervalos usuais de monitoramento para validação de créditos de carbono (geralmente entre 30 e 40 anos), reforçando a aplicabilidade prática do framework para o planejamento e a verificação de projetos sob esquemas de mitigação climática.

Por fim, ressalta-se que os métodos empregados neste estudo são replicáveis e escaláveis para outros contextos tropicais, desde que se disponha de dados regionais minimamente estruturados. Em um cenário de emergência climática, a adoção de abordagens orientadas por atributos funcionais oferece uma oportunidade concreta para acelerar o acúmulo de carbono em projetos de restauração ecológica, promovendo soluções baseadas na natureza com alto impacto e viabilidade prática. Os resultados deste estudo também dialogam com políticas e metas globais de restauração, como o *Bonn Challenge*, o *Global Biodiversity Framework* e a Década das Nações Unidas da Restauração de Ecossistemas (ONU, 2021), bem como com iniciativas nacionais como o PLANAVEG. Ao demonstrar o potencial das abordagens funcionais para acelerar o sequestro de carbono e ampliar a diversidade funcional, este trabalho oferece subsídios técnicos valiosos para orientar a priorização de espécies e o planejamento de projetos em larga escala.

A restauração baseada em atributos funcionais permite otimizar o tempo de acúmulo de carbono e gerar co-benefícios, como maior diversidade de espécies, contribuindo para a integração entre avanços teóricos e aplicabilidade prática na restauração de ecossistemas tropicais.

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