UFRJ

CIRO JOSÉ RIBEIRO DE MOURA

MONITORAMENTO DA RESTAURAÇÃO FLORESTAL ATRAVÉS DA UTILIZAÇÃO DE METODOLOGIAS CONVERGENTES.

Rio de Janeiro
2023

Ciro José Ribeiro de Moura

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Tese de Doutorado apresentada ao Programa de Pós-Graduação em Engenharia Ambiental da Escola Politécnica e Escola de Química da UFRJ.

Orientadora:

Maria Fernanda S. Quintela da Costa Nunes

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Sumário

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Gostaria de expressar meus sinceros agradecimentos a todos aqueles da comunidade da Restauração Ecológica ao longo dos anos que perseveram e lutam contra a entropia e em prol dos nossos ecossistemas nativos.

Agradeço enormemente aos meus colegas e companheiros de profissão Julia Bochner e Flávio Valente que me convidaram para retornar ao Inea, em um projeto na Gerencia do Serviço Florestal (GESEF) para ajudar na criação de um modelo de gestão para a restauração florestal no Estado do Rio de Janeiro. Sem eles provavelmente meus caminhos teriam sido diferentes.

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EPÍGRAFE

"Sucede que a floresta não pode dizer. A floresta não anda. A selva fica onde está. Fica à mercê do homem...”

Thiago de Mello

1 INTRODUÇÃO

A Convenção da Diversidade Biológica (CDB, 1992) recomenda às nações ao redor do mundo, que meçam seus progressos em torno de seus objetivos de conservação da biodiversidade, sobretudo aqueles ligados as perdas de biodiversidade ou em resposta a elas. Neste sentido, a CDB sugere que os países desenvolvam ferramentas, dispositivos, legislações e formas de medir e manejar sua biodiversidade.

Analisando a CBD, Collen et al. (2014) recomenda que as pesquisas sobre biodiversidade devam considerar as lacunas de conhecimento acerca da biodiversidade, especificamente no desenvolvimento de métodos que consideram amostras representativas e em escala, com foco em áreas chaves para a conservação. Os autores ainda afirmam que investimentos devem ser direcionados a iniciativas que possam desenvolver infraestrutura e expertise para o monitoramento em larga escala.

Considerando o monitoramento como elemento fundamental da engenharia ambiental e da conservação da biodiversidade, e que a restauração florestal é instrumento para a manutenção da qualidade ambiental no planeta, a Sociedade Internacional de Restauração Ecológica (SER) produziu o referencial teórico (SER Primer, 2004) onde apresenta os critérios para avaliação e monitoramento da restauração e aponta os atributos a serem observados na avaliação de ecossistemas em processo de restauração.

O monitoramento em páreas em processo de restauração florestal pode ser entendido como a mensuração periódica de indicadores ou variáveis ambientais, em áreas em processo de restauração, visando avaliar sua trajetória ecológica ou outros objetivos específicos (Belotto et al. 2010).

Em estudo sobre projetos de monitoramento Ruiz-Jaen e Aide (2005), avaliaram o uso dos atributos recomendados pelo documento referencial SER Primer (2004) e concluíram que os critérios para avaliar o sucesso de restauração devem ser baseados em uma comparação com mais de um local de referência para fornecer as dinâmicas temporais e espaciais dos ecossistemas.

Monitorar a restauração ecológica tem sido historicamente dependente de métodos tradicionais de inventário baseados em informações detalhadas obtidas de parcelas de campo. Novos paradigmas são agora necessários para alcançar com sucesso a restauração como um processo transformador em larga escala e duradouro (Almeida et al. 2020)

As formas de monitorar podem ser através de comparação direta com o ecossistema de referência; avaliação de atributos com base nos objetivos da restauração ou por análise da trajetória onde os dados coletados são utilizados na avaliação periódica da evolução em direção ao ecossistema de referência (Suganuma e Durigan 2015).

2 REVISÃO DE LITERATURA

2.1 Monitoramento da restauração florestal no Brasil

O Brasil é um dos países com maior diversidade biológica do mundo, e a conservação e a restauração das florestas são fundamentais para a manutenção da biodiversidade, bem como para a mitigação das mudanças climáticas (Metzger 2019). A restauração florestal consiste em plantar árvores em áreas que foram degradadas ou desmatadas, com o objetivo de recuperar as funções ecológicas dessas áreas (Rodrigues 2020).

No Brasil, a restauração florestal é regulamentada pelo Código Florestal, que estabelece regras para a recuperação de áreas degradadas. Além disso, existem iniciativas governamentais e privadas para promover a restauração florestal em todo o país, como o Programa de Recuperação Ambiental (PRA) e o Programa Agricultura de Baixo Carbono (ABC) (Tejerina et al. 2021).

No entanto, a implementação da restauração florestal no Brasil enfrenta desafios significativos, como a falta de recursos financeiros e tecnológicos, a falta de conhecimento técnico, a dificuldade de encontrar sementes de espécies nativas e a falta de incentivos para os proprietários de terras.

O monitoramento da restauração florestal no Brasil é fundamental para avaliar a efetividade das ações de restauração e para identificar oportunidades de melhoria. Existem várias iniciativas de monitoramento em andamento nos Estados. Essas iniciativas utilizam técnicas como o sensoriamento remoto e a análise de imagens de satélite para avaliar a cobertura vegetal e o progresso da restauração em diferentes regiões do país.

Nesse sentido, é necessária uma estrutura analítica para calcular taxas de compensação que garantam ganhos de conservação em áreas restauradas para evitar a perda de biodiversidade no longo prazo (Moilanen et al. 2009).

No Brasil a Lei Federal Nº 12.651 de 25 de maio de 2012, intitulada Lei de Proteção da Vegetação Nativa (LPVN), prevê programas de controle e incentivo à preservação e conservação florestal, estabelecendo diversos mecanismos de controle como o Cadastro Ambiental Rural (CAR), o Programa de Regularização Ambiental (PRA), o Projeto de Recuperação de Terras Degradadas e Alteradas (PRADA) e o programa de Cotas de Reserva Ambiental (CRA), permitindo uma abordagem de gestão integrada, indo além do monitoramento e fiscalização (Brancalion e Chazdon 2017).

A heterogeneidade ambiental do Brasil já é um desafio, e os governos estaduais poderiam estabelecer instrumentos legais para determinar e referenciar sucessos de restauração para cada tipo de ecossistema, que contempla todo o processo de restauração, ou seja, entre o plantio e o estabelecimento de uma nova floresta (Maron et al. 2012). Atualmente no Brasil, as regulamentações ambientais resultam basicamente de políticas de centralização e planejamento conduzidas pelos Estados de cada um dos países.

Os resultados mostram que as regulamentações mais recentes foram exigidas por uma sociedade civil cada vez mais consciente do ponto de vista ambiental e mais organizada, por meio de quadros políticos mais participativos e democráticos e melhores conhecimentos e exigências científicas (Drummond e Barros-Platiau 2006).

2.1.1 Enquadramento jurídico brasileiro

A Implementação efetiva A Lei Federal Brasileira nº 12.651 de 25 de maio de 2012, formalmente intitulada Lei de Proteção da Vegetação Nativa (LPVN), consiste em um desafio enorme. O primeiro desafio crucial é convencer o setor do agronegócio dos ganhos potenciais com a restauração florestal e seus serviços ecossistêmicos associados (Soares-Filho et al. 2014)

A Lei Federal Brasileira nº 12.651 de 25 de maio de 2012, formalmente intitulada Lei de Proteção da Vegetação Nativa (LPVN), prevê programas de controle e incentivo para facilitar e promover a preservação e conservação das florestas, estabelecendo diversos mecanismos de controle como o Cadastro Ambiental Rural (CAR), o Programa de Regularização Ambiental (PRA), o Projeto de Recuperação de Terras Degradadas e Alteradas (PRADA) e o programa de Cotas de Reserva Ambiental (CRA), contemplando uma gestão integrada, indo além do simples monitoramento e fiscalização (Brancalion et al. 2016).

O LPVN determina que toda propriedade rural privada deva destinar um percentual de sua área total para conservação e manejo florestal em um instrumento legal denominado “Reserva Legal” (RL). Isso varia por bioma; 80% na Amazônia, 35% nos cerrados e 20% em todos os outros biomas, como Mata Atlântica e Pantanal. O objetivo da RL é oferecer um uso econômico e sustentável dos recursos naturais da propriedade rural, promovendo a conservação da biodiversidade (Chaves et al. 2015).

Ainda existe uma previsão na lei que inclui áreas para restauração denominadas de Áreas de Preservação Permanente (APP), que são áreas em zonas de amortecimento ciliar ao longo de córregos e ao redor de nascentes, em encostas superiores a 45° e topos de morro onde a restauração é obrigatória (Calmon e outros, 2011).

A LPNV também criou um protocolo on-line integrado para regular o cumprimento da legislação ambiental e planejar o uso produtivo das propriedades rurais. Todos os proprietários de terras devem cadastrar suas propriedades no sistema denominado “Cadastro Ambiental Rural” (CAR), no qual devem ser declaradas todas as APPs e RLs cobertas ou não por vegetação nativa, bem como as áreas produtivas.

2.1 Monitoramento da restauração florestal em campo

O reconhecimento da necessidade de um modelo de monitoramento e avaliação de projetos de restauração é parte importante para o sucesso do gerenciamento destas iniciativas (Vallauri et al. 2005). Porém os desafios para sua implementação são um desafio para a gestão ambiental, cientistas e criadores de políticas públicas. O Pacto pela Restauração da Mata Atlântica (PACTO, 2009) uma das mais importantes iniciativas não governamentais apoio a restauração florestal nos trópicos, desenvolveu um robusto protocolo com 87 indicadores que englobam aspectos biológicos, econômicos, sociais, legais, ambientais e temas de manejo (Melo et. al. 2014).

A restauração florestal é uma das estratégias mais eficazes para prevenir a perda de biodiversidade (Ditt et al. 2010; Bullock et al. 2011; Tonetti et al. 2022) e um método importante para a conservação da biodiversidade in situ. Para cumprir as metas de conservação da biodiversidade (Myers et al. 2000), são necessários acordos de mudança climática e compromissos internacionais ambiciosos para implementar a restauração florestal e paisagística (FLR), juntamente com conscientização política e mobilização financeira (Brancalion e Chazdon 2017).

No entanto, para garantir a qualidade dos esforços de restauração florestal, o monitoramento e a avaliação devem fazer parte das rotinas de projetos e programas para gerenciar e verificar resultados e realizações (DeLuca et al. 2010; de Souza e Batista 2004).

A restauração ecológica é utilizada como estratégia para compensar a perda de biodiversidade causada pelas atividades humanas (Maron et al. 2012). Além disso, a restauração ecológica desempenha um papel fundamental na abordagem dos desafios da sustentabilidade e das mudanças climáticas (Scheidel e Gingrich 2020). Essa estratégia envolve o equilíbrio da perda de biodiversidade em um local por um ganho de biodiversidade equivalente em outro lugar, mas essa compensação simplista tem profundas implicações. A compensação da biodiversidade em todo o mundo tornou-se um requisito regulatório e pode ser alcançada por meio de transações comerciais de “créditos” de biodiversidade, embora sua eficiência ambiental e conveniência social permaneçam obscuras (Bonneuil 2015).

O problema essencial reside aí, pois a perda de biodiversidade devido ao desenvolvimento pode ser subestimada e a legislação pode ser melhorada para evitar consequências não intencionais (Apostolopoulou e Adams 2017).

Mansourian et al. (2020) destacam a necessidade de uma mudança nos processos de tomada de decisão para restauração florestal em larga escala, visando uma melhor compreensão das motivações e objetivos das partes interessadas e a necessidade de equilíbrio entre planejamento e flexibilidade para aumentar a resiliência socioecológica.

A eficácia da restauração florestal em paisagens dominadas pelo homem, como o bioma Mata Atlântica brasileira, onde vivem pelo menos 70% da população brasileira (Metzger 2009) com alta dependência de serviços ecossistêmicos, precisa ser monitorada e avaliada para garantir a conservação do bioma, abastecimento de água, produção de alimentos, entre outros serviços prestados pelas florestas (Benayas et al. 2009; Calmon et al. 2011). Avaliar o sucesso dos projetos de restauração florestal é fundamental para selecionar as melhores práticas e estratégias para promover o manejo de recursos naturais (Wortley et al. 2013). De igual importância é a determinação e avaliação dos riscos assumidos em projetos de restauração florestal, especialmente em relação ao controle e mensurabilidade deficientes, longos intervalos de tempo e cenários imprevisíveis (Maron et al. 2012).

Portanto, um sistema de monitoramento adequado é essencial para apoiar a tomada de decisões e acompanhar os resultados da restauração (Nilsson et al. 2016). Além disso, a comparação estratégica com locais de referência é crucial durante a avaliação (Lawley et al. 2016). No entanto, geralmente não é viável monitorar diretamente todos os atributos e funções importantes da floresta, sendo necessário selecionar alguns indicadores (Burton 2014).

Além disso, todos os indicadores devem representar as condições atuais e ser responsivos para orientar a gestão do projeto de restauração. Eles também devem ser robustos o suficiente para avaliar uma área independentemente da técnica utilizada para iniciar o processo de restauração. Além disso, os indicadores devem ser integrativos e permitir ao tomador de decisão inferir sobre a trajetória ecológica e o funcionamento do ecossistema.

A Sociedade Internacional para Restauração Ecológica estabeleceu nove atributos de ecossistema que podem ser usados como diretrizes para avaliar o sucesso da restauração (Clewell et al. 2004). A SER sugeriu: diversidade e estrutura comunitária semelhantes em comparação com locais de referência; a presença de espécies indígenas; a presença de grupos funcionais necessários para a estabilidade a longo prazo; a capacidade do ambiente físico para sustentar populações reprodutivas; funcionamento normal; integração com a paisagem; eliminação de ameaças potenciais; resiliência a perturbações naturais; autosustentabilidade.

Embora a medição desses atributos possa fornecer uma excelente avaliação do sucesso da restauração, poucos estudos têm recursos financeiros para monitorar todos esses atributos. Além disso, as estimativas de muitos atributos geralmente requerem estudos detalhados de longo prazo, mas a fase de monitoramento da maioria dos projetos de restauração raramente ultrapassa os 5 anos (Ruiz-Jaen e Aide 2005).

A definição dos atributos deve ainda estar atreladas aos objetivos do projeto ou programa de restauração, que podem ser o a necessidade ou obrigação no cumprimento de demandas legais; pesquisa científica; produção madeireira e não-madeireira; serviços ecossistêmicos (carbono, água, biodiversidade); conservação de espécies/populações; aspectos socioeconômicos; avaliação da trajetória ecológica (Viani et al. 2013).

É relevante considerar que os resultados da restauração florestal hoje estão no contexto do Antropoceno (Coombs 2014), que é diametralmente diferente de uma floresta virgem idealizada (Stanturf et al. 2014). Nesse sentido, a maioria das florestas tropicais está se tornando ecossistemas alterados, nos quais o grau de alteração depende da intensidade e duração das pressões antrópicas (Malhi et al. 2014). Portanto, é necessário distinguir diferentes tipos de povoamentos de reflorestamento com base em suas origens, propriedades dinâmicas e configurações da paisagem (Chazdon et al.

2016), e o sistema de monitoramento deve considerar essas diferenças e ser orientado por objetivos (Noss 1999).

Atualmente, a eficácia dos programas de restauração promovidos na América Latina depende de sua integração com estruturas e organizações nacionais e subnacionais de restauração, que podem ser apoiadas por redes de restauração (Meli et al. 2017). Ao mesmo tempo, a restauração florestal em larga escala enfrenta desafios como provar sua eficácia ecológica, a ausência de ferramentas para apoiar os processos de tomada de decisão e outros fatores (Brancalion e Chazdon 2017). O processo de tomada de decisão precisa do apoio de ferramentas e estruturas que devem ser integradas às políticas públicas destinadas a promover e garantir a restauração florestal (Durigan et al. 2010; Assis et al. 2013), fornecendo regras claras que podem ser mais eficazes do que financeiras incentivos para restauração florestal.

Usualmente o monitoramento da restauração florestal se inicia na seleção de indicadores ecológicos que serão utilizados nos levantamentos de campo, e que posteriormente deverão ser utilizados no diagnóstico ambiental.

Os indicadores ecológicos são variáveis cuja finalidade é medir alterações em um fenômeno ou processo do ecossistema e podem ser qualitativos, obtidos de forma não mensurável, com base na observação e julgamento do observador ou quantitativos que partem da mensuração direta de determinados descritores da área em processo de restauração (Busch et al. 2012).

Outra abordagem a ser considerada em relação aos indicadores é relativa ao tipo de evento a ser descrito, podendo ter uma abordagem em termos de diversidade, espécies e grupos funcionais que integram o ecossistema; ou relacionados a estrutura que explicam como a comunidade vegetal está organizada espacialmente; e ainda uma abordagem relativa ao funcionamento do novo ecossistema, focada no restabelecimento dos processos ecológicos que permitem autoperpetuação do ecossistema (Dale e Beyeler 2001). Outros atributos podem e devem ser avaliados conforme as possibilidades de cada projeto, como indicadores econômicos e sociais (Wortley et al. 2013).

Cabe ressaltar que um bom indicador deve ser sensível em termos de responder no tempo aos fatores que atuam sobre o ecossistema; possibilitar predições dos efeitos da degradação ou de práticas de restauração sobre o ecossistema; deve ainda ser integrativo, representando na medida do possível outras variáveis mais difíceis de medir; além de ser de fácil medição (rápido, simples e barato) e de fácil interpretação (Dale e Beyeler 2001)

A experiência de monitoramento intensivo está de certa forma bem estabelecida na Europa, por exemplo, entretanto alguns desafios ainda persistem como afirmam Ferretti e Chiarucci (2003) que indicam a análise e avaliação dos dados em protocolos bem estabelecidos, a escolha de indicadores e a estratégia de amostragem como problemas a serem resolvidos pela pesquisa. Ferretti e Chiarucci (2003) afirmam ainda que os monitoramentos realizados em campo, não permitem análises na escala de grandes paisagens.

Outra perspectiva é apresentada por Garcia e Lescuyer (2008) que consideram que o ganho de escala no monitoramento de florestas passa pelo envolvimento das comunidades locais, onde a real implementação do monitoramento pode ser obtida com a participação dos interessados diretos, ou seja, as comunidades locais. No entanto, primeiro é necessário desenvolver uma estratégia para organizar este conhecimento empírico.

Wortley (2013) sugere que a evidência empírica poderia ser usada para apoiar o acompanhamento da restauração florestal sendo esta, uma tendência que deveria ser objeto de mais pesquisas. Além disso, os resultados empíricos podem ser conferidos a restauração florestal através da utilização de protocolos especialmente desenvolvidos e podem promover e fornecer informações valiosas para avaliar estado de ecossistemas e da eficácia de gestão (Tierney, 2009).

2.2 Monitoramento da restauração florestal através de sensores remotos

O monitoramento da restauração florestal utilizando sensoriamento remoto é uma ferramenta muito importante e eficaz para avaliar o progresso da restauração em áreas degradadas. A técnica de sensoriamento remoto utiliza imagens de satélite para coletar dados sobre a cobertura vegetal, a topografia, a umidade do solo e outros parâmetros ambientais em uma determinada área (Balieiro 2019).

O uso sensoriamento remoto permite avaliar a evolução do processo de restauração ao longo do tempo, bem como identificar áreas que precisam de mais atenção ou que estão apresentando resultados positivos. A análise desses dados também pode ajudar a identificar as espécies de árvores mais adequadas para cada região, bem como a avaliar a eficácia das técnicas de plantio utilizadas.

Embora a pesquisa descreva bem o monitoramento florestal no campo, as técnicas de sensoriamento remoto não atingiram o seu potencial como ferramenta para o monitoramento de florestas apesar de suas possibilidades para superar os desafios e a necessidade do ganho de escala no processo.

Aeronaves remotamente pilotadas (RPA), popularmente conhecidas como drones, se apresentam como ferramentas promissoras no monitoramento de projetos de Restauração Florestal, entretanto os reais benefícios que o RPA pode proporcionar ainda demandam mais estudos que promovam os avanços necessários nas metodologias e nas técnicas de sensoriamento remoto aplicados a restauração florestal (Viani et al. 2021).

As medições de sensoriamento remoto através do uso de RPAs são um substituto econômico para as medidas de campo tradicionais e consistem em uma metodologia de sensoriamento remoto baseada em UAV de baixo custo (Zahawi et al. 2015).

Tecnologias como uso de radares, LiDAR (Light Detection and Ranging) e diferentes sensores óticos, podem ser complementados ao uso tradicional da imagem aérea fotogramétrica. As vantagens destes métodos são o acesso rápido aos dados, integração com plataformas de dados de Sistemas de Informações Geográficas (SIG) e, por conseguinte processamento de grande quantidade de informações e ganho de escala (Suarez et al. 2003).

Através do monitoramento contínuo e do uso de técnicas de sensoriamento remoto e mapeamento baseados em foto interpretação, e uso de imagens de alta resolução através de técnicas de classificação supervisionada de objetos pode alcançar objetivo do monitoramento de larga escala (Almeida, 2020). Freeman e Buck (2003) afirmam que o uso de classificações com base no sensoriamento remoto ainda demanda um grande esforço e consomem muito tempo, e que a solução para este gargalo está no desenvolvimento de técnicas automáticas ou semiautomáticas.

O esforço para o desenvolvimento de ferramentas de sensoriamento remoto, voltadas a necessidade de avanços no monitoramento ambiental, são coerentes com as metas de conservação descritas na CDB (1992) e a aplicação de um sistema de ordenamento e classificação supervisionada de objetos precisa ser desenvolvido, fornecendo soluções operacionais que podem apoiar a tomada de decisão a partir de dados de sensoriamento remoto (Blaschke 2010).

O campo da ecologia espacial é está passando por uma revolução em face dos avanços e do aumento de capacidade operacional e eficácia do monitoramento e manejo dos recursos naturais com o uso de drones, devido ao fato de voarem em baixas altitudes e coletar imagens em altíssima definição e de forma acessível, criando novas oportunidades para medição de fenômenos ecológicos em escala apropriada (Anderson e Gaston, 2013).

Portanto, a partir da perspectiva das práticas de monitoramento da restauração florestal (PACTO 2013) e do potencial do uso de sensoriamento remoto no monitoramento da restauração de ecossistemas.

O uso de imagens de satélite de alta resolução, com toda sua riqueza de informações podem contribuir para a melhoria no monitoramento da restauração florestal, tornando possível uma análise em uma escala da paisagem, quando comparada aos métodos tradicionais de monitoramento por imagens, com suas limitações (Ferretti e Chiarucci 2003).

A necessidade de se desenvolver novos métodos de classificação que incluam dados auxiliares e conhecimentos específicos utilizando uma abordagem orientada ao objeto tornou-se muito indicada para estes tipos de estudo de monitoramento e avaliação, especialmente por causa de sua capacidade de extrair objetos de interesse com maior precisão do que os métodos com base em pixel (Ribeiro e Kux 2009).

Neste sentido, aproximar a realidade de campo e o uso de imagens de sensores remotos com metodologias convergentes é fundamental para que se possa ganhar escala no monitoramento da restauração florestal.

3 OBJETIVOS

Descrever e analisar leis, decretos, regulamentos, resoluções e mandatos institucionais vinculados à legislação em vigor e às mais recentes regulamentações sobre restauração ecológica no Brasil, com a introdução da existência de protocolos de monitoramento nos 27 estados brasileiros.

Desenvolver e consolidar metodologias de monitoramento da restauração florestal através de diferentes abordagens incluindo a integração de sensoriamento remoto.

Analisar e avaliar os indicadores ecológicos utilizados em um protocolo de monitoramento aplicado na avaliação de projetos de restauração florestal do Instituto Estadual de Meio Ambiente do Rio de Janeiro.

3.1 Objetivos específicos:

- Avaliar o estado da arte no monitoramento da restauração florestal nos estados brasileiros.
- Desenvolver métodos integrados para monitorar projetos de restauração florestal assumindo três características básicas: baixo custo, método automatizado e com precisão.
- Avaliar a correlação entre a classificação de parâmetros ecológicos através do uso de tecnologias de sensoriamento remoto.
- Avaliar o nível de precisão e as diferenças entre classificações dos levantamentos de campo e o sensoriamento remoto.

4 CAPITULO 1 NORMAS REGULATÓRIAS SÂO SUFICIENTES PARA ALAVANCAR A RESTAURAÇÃO FLORESTAL? UM ESTUDO DE CASO BRASILEIRO

5 CAPITULO 2 UM NOVO PROTOCOLO DE MONITORAMENTO PARA AVALIAR PROJETOS DE RESTAURAÇÃO FLORESTAL EM LARGA ESCALA NOS TRÓPICOS

6 CAPITULO 3 FOREST RESTORATION MONITORING PROTOCOL WITH A LOW-COST REMOTELY PILOTED AIRCRAFT: LESSONS LEARNED FROM A CASE STUDY IN THE BRAZILIAN ATLANTIC FOREST

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Article

Are Regulatory Standards Enough to Leverage Forest Restoration? A Brazilian Case Study

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ABSTRACT

Environmental offsetting is a compensation for a deforested or degraded area usually in the form of forest recovery. We provide an update on the ongoing regulatory standards (RS) regarding ecological restoration in Brazil, analyzing the existence of monitoring protocols. The introduction of Environmental Rural Registry (CAR) created by law in 2012 has become the main driver of local RS. The aim of CAR is to guarantee forest cover on rural properties by the force of RS, but it lacks to consider the vegetation structure, functionality, and quality of the vegetation. Currently only four states in Brazil uses a protocol that includes ecological criteria as a measurement of success. The existence of a specific legislation for forest restoration may enhance restoration effectiveness by clarifying the restoration process and regulations to those stakeholders involved in implementing restoration projects. It is necessary for RS to include diverse technical approaches, providing the opportunity for solutions contemplating local possibilities and conditions.

Keywords: ecological restoration policy; environmental adequacy; regulatory standards.

RESUMO

A compensação ambiental de áreas desmatadas ou degradadas, geralmente acontece na forma de restauração florestal. Este trabalho traz a atualização sobre as normas regulatórias (NR) em vigor sobre restauração ecológica no Brasil, analisando a existência de protocolos de monitoramento. A implantação do Cadastro Ambiental Rural (CAR), criado por lei em 2012, passou a ser o principal impulsionador do surgimento de NR no nível local. O objetivo do CAR é garantir a cobertura florestal nas propriedades rurais pela força do RS, mas falta considerar a estrutura da vegetação, a funcionalidade e a qualidade da vegetação.Atualmente, apenas quatro estados do Brasil utilizam protocolos que incluem critérios ecológicos como medida de sucesso. A existência de uma legislação específica para restauração florestal pode aumentar a eficácia da restauração, esclarecendo o processo de restauração e os regulamentos para as partes interessadas envolvidas na implementação de projetos de restauração. É necessário que as NR considerem abordagens técnicas diversas, oportunizando soluções que contemplem as possibilidades e condições locais.

Palavras-chave: política de restauração ecológica; adequação ambiental; padrões regulatórios.

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Introduction

Ecological restoration is used as a strategy to compensate for biodiversity loss caused by human activities (Maron et al., 2012). Furthermore, ecological restoration plays a key role in addressing sustainability challenges and climate change (Scheidel and Gingrich, 2020). This strategy involves the balancing of biodiversity loss in one place by an equivalent biodiversity gain elsewhere, but this simplistic compensation has profound implications. Worldwide biodiversity offsetting has become a regulatory requirement and can be achieved via commercial transactions of biodiversity "credits" though its environmental efficiency and societal desirability remain unclear (Bonneuil, 2015).

The essential problem lies there in, as the biodiversity loss due to development may be underestimated and legislation could be improved to avoid unintended consequences (Apostolopoulou and Adams, 2017). In this sense, an analytic framework for calculating offset ratios that guarantee conservation gains in restored areas is required to avoid biodiversity loss in the long run (Moilanen et al., 2009).

In Brazil the Federal Law Nº°12.651 of May 25th, 2012, entitled Native Vegetation Protection Law (LPVN), provides programs of control and encourages forest preservation and conservation, establishing various mechanisms of control such as the Environmental Rural Registry (CAR), the Environmental Compliance Program (PRA), the Project for Recovery of Degraded and Altered Land (PRADA), and the Environmental Reserve Quotas program (CRA), allowing for an integrated management approach, advancing beyond monitoring and enforcing compliance (Brancalion and Chazdon, 2017).

The environmental heterogeneity of Brazil, is already a challenge, and, the state governments could establish legal instruments to determine and reference restoration successes for each ecosystem type, that contemplates the entire restoration process, i.e. between the planting and the establishment of a new forest (Maron et al., 2012). Currently in Brazil, environmental regulations result basically from centralization and planning policies conducted by each of the countries' State. Results show that most recent regulations were demanded by a an increasingly environmentally aware and more organized civil society, through more participatory and democratic political frameworks and improved scientific knowledge and requirements (Drummond and Barros-Platiau, 2006).

In this paper, we describe and analyze laws, decrees, regulations, resolutions, and institutional mandates linked to ongoing legislation and the most recent regulations regarding ecological restoration in Brazil, with the introduction of the existence of monitoring protocols in Brazil's 27 States.

Material and methods

Legal framework

The Brazilian Federal Law nº12.651 of May 25th, 2012, formally entitled Native Vegetation Protection Law (LPVN), provides programs of control and incentive to facilitate and promote forest preservation and conservation, establishing various mechanisms of control such as the Environmental Rural Registry (CAR), the Environmental Compliance Program (PRA), the Project for Recovery of Degraded and Altered Land (PRADA), and the Environmental Reserve Quotas program (CRA), contemplating an integrated management approach, advancing beyond simple monitoring and enforcing compliance (Brancalion et al., 2016).

The LPVN determines that every rural private property has to set aside a percentage of its total area for forest conservation and management in a legal instrument called the "Legal Reserve" (RL). This varies per Biome; 80% in the Amazon, 35% in the Brazilian savanna (cerrados) and 20% in all other biomes, as Atlantic Rainforest and Pantanal. The RL aim is to offer some economic and sustainable use of the rural property's natural resources whilst promoting biodiversity conservation (Chaves et al., 2015).

There is still a provision in the law which includes areas for restoration called Permanent Preservation Areas ("APP" in Portuguese), which are areas in riparian buffer zones along streams and around springs, on slopes greater than 45 ° and hilltops where restoration is mandatory (Calmon et al., 2011).

The LPNV also created an integrated online protocol for regulating environmental legal compliance and planning the productive use of rural properties. All landowners have to register their properties in the system known as "The Environmental Rural Register" (CAR in Portuguese), in which all APPs and RLs whether covered or not by native vegetation have to be declared, as well as productive areas in a geodatabase. Owners of landholdings with less native vegetation cover than the minimum required by law are obliged to implement restoration, and invited to adhere to the "Environmental Regularization Program" (PRA).

Legislation survey

The data used in this study was obtained in cooperation with the Brazilian Network for Ecological Restoration, also called REBRE (Isernhagen et al., 2017), consulted on the legal database of each of the 27 Brazilian states for CAR validation, or was provided or indicated by specialists spread across Brazil

For this study, we surveyed the regulatory standards of forest restoration in Brazil consulting the government's databases that guide two main drivers of forest restoration in Brazil; the Brazilian Federal Law 12.651/2012 (LPNV), and local regulations of environmental offsetting. In addition, we referred to the forecasts of monitoring as an indication of protocols to follow up restoration projects. We consider a regulatory standard as a benchmark promulgated by a regulatory agency, created to enforce the provisions of legislation.

Geodatabse survey

The geodata was collected on the National Database of Environmental Rural Registry (SICAR) of the State of Rio de Janeiro. It includes the spatial information of all rural properties and their environmental liabilities pointed automatically by the SICAR system. This is available at: http://www.car.gov.br/

The decision to restrict analysis of restoration projects occurring in the state of Rio de Janeiro is due to access to the environmental offsetting legislation database in a website: https://www.restauracaoflorestalrj.org/

Data analysis

We verified the existence or absence of legislation and its driver that can be the LPVN or offsetting policies (OP) as the following list: Federation State; Existence of legislation; LPVN legislation; OP legislation; Synergy of LPVN x OP; Restoration Method Prediction (RMP); RMP | Natural regeneration; RMP | Enrichment; RMP | Nucleation; RMP | Seedling;

RMP | Planting; RMP | Agroforestry; RMP | Mixed plantations; RMP | Topsoil transposition; Monitoring forecast; Deadline forecast; Monitoring protocol; Remote sensing monitoring; Self-monitoring; Self-monitoring methodology.

The collected information was organized into a spreadsheet where each parameter was verified for each of the 27 Brazilian states. The information was verified by reviewing the ongoing legislation and norms founded for each state.

The analysis of the geo database obtained on SICAR, and the maps were made on the software QGIS 3.12.1.

The data collection includes diverse ecosystem types as the Brazilian Atlantic Forest (Mata Atlântica) and Brazilian Savanna (Cerrado) biomes, recognized as global biodiversity hotspots (Myers et al., 2000).

Results and discussion

Since the launch of the Federal Decree nº 7.830 in 2012 which regulates the Environmental Rural Registry (CAR), this study found a positive correlation (R^2=0,968) in the number of local legislations linked to the Environmental Regularization Program (PRA). We found that 19 states have legislation in compliance with the PRA and the LPVN. In 2011, before the introduction of the CAR, only 2 states had forest restoration legislation in place that specifically applied for the environmental offsetting regulation.

This increment of regulatory standards since 2012 consolidated as an innovative tool for land-governance and environmental policies in Brazil creating conditions for developing an efficient monitoring system to determine critical deforestation areas, integrated government and NGO's efforts, and heavy investments from national and international funding agencies (Roitman et al., 2018).

The rising of new RS of forest restoration creates an unprecedented opportunity for implementing large-scale strategies that should be designed considering ecological aspects, but also socioeconomic matrix interests and uses of landscape to expand project strategies and methodologies while also supporting a more effective, long-lasting and inclusive restoration (Siqueira et al., 2021).

Our results indicate the increase of regulatory standards in Brazil, with a new scenario that comes with the emergence of PRA, and, 70,37 % of the Brazilian States have it as the sole policy with regulation regarding ecological restoration. With PRA and Offsetting considered, 92,5% of the States have regulatory standards as just two states have no standards established as shown on Fig. 1 and Fig. 2.

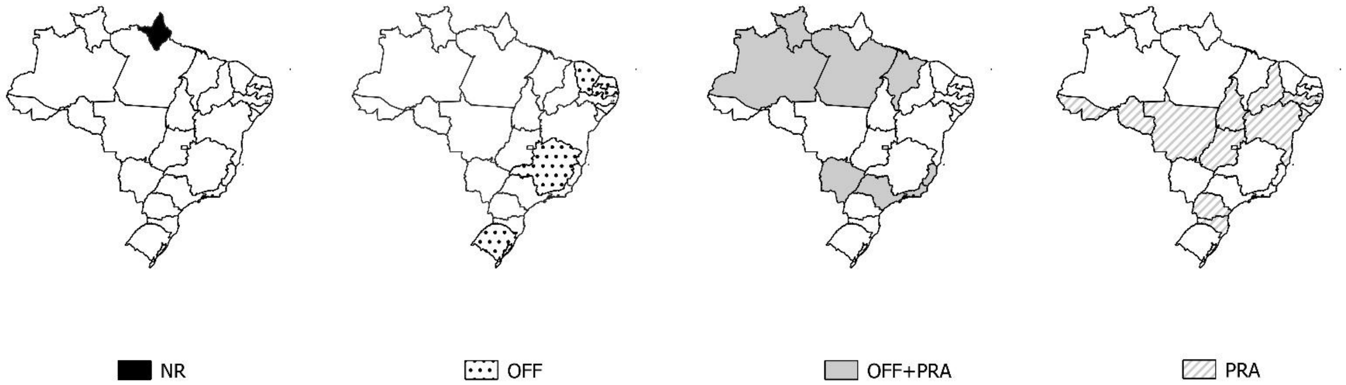

Fig.1. Brazilian states with associated regulatory standard drivers of forest restoration. Where: NR: no regulation; OFF: offsetting policy; PRA: Environmental Compliance Program.

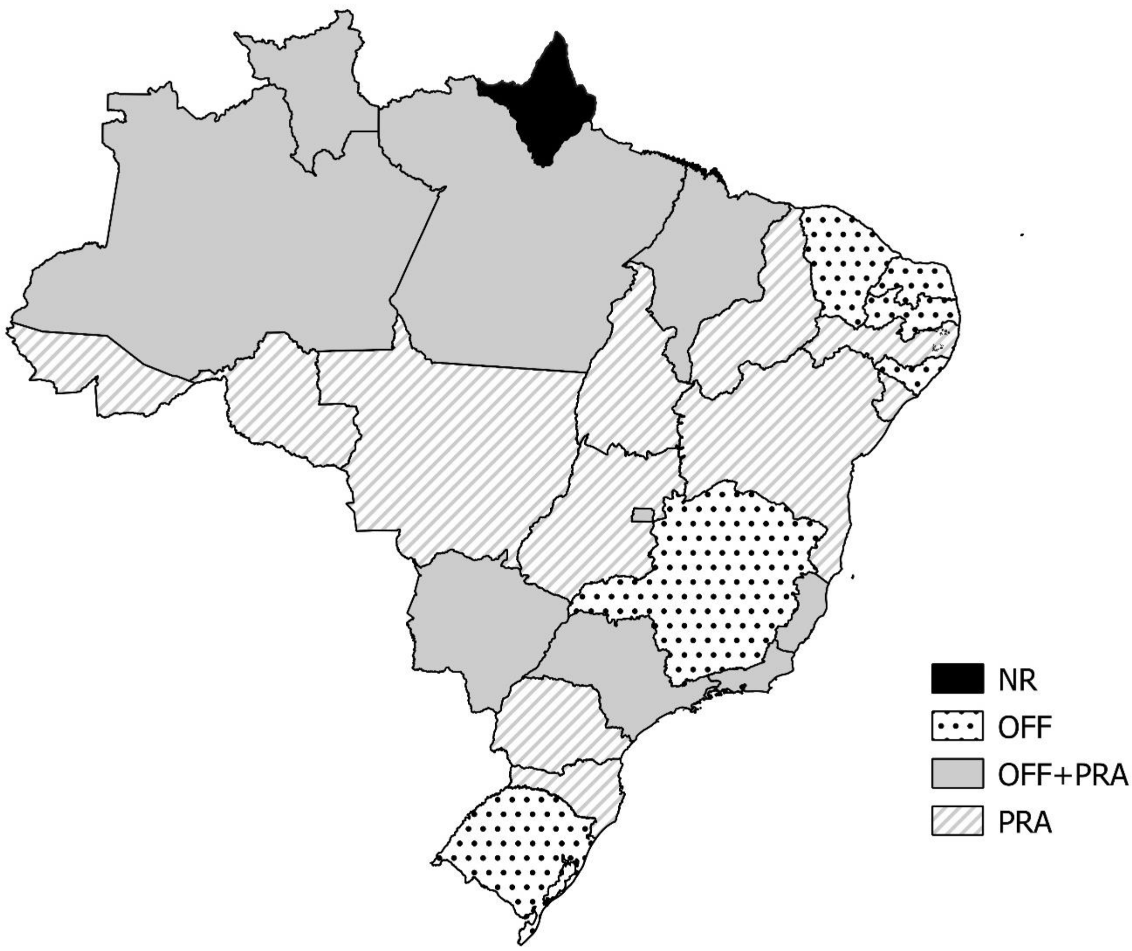

Fig.2. Brazilian states with regulation associated with forest restoration. Where: NR: no regulation; OFF: offsetting policy; PRA: Environmental Compliance Program.

Just four states have an established protocol of monitoring, although this activity is expected by 48,1% of the actual regulation. As, the current aim is to increase forest cover, with virtually no references on the regulatory standards to indicators of vegetation structure and functionality. Pacheco et al. (2021) indicate that the improvement of regulatory standards about forest restoration can contribute to the availability and quality of natural resources such as ecosystem services and biodiversity depend on the conservation and restoration of native vegetation.

Considering that ecosystem restoration is a long-term process, the evaluation of each stage of its trajectory may allow us to predict the success of the restoration goals. Given that there are plenty of indicators in the scientific literature for measuring restoration success, and there are stakeholders who are the key actors of restoration, is desirable to determine a common and simple set of indicators ranked by stakeholders for evaluating the restoration trajectory (Oliveira et al. 2021).

Despite the monitoring forecast on ongoing legislation, there is a clear gap in the absence of monitoring protocols, existing in only 4 states or 18% of the total of existing regulations.

Monitoring forest restoration projects are very useful when applied, especially in the context of offset policies intended to achieve serious compensation for environmental degradation or loss of biodiversity (Chaves et al. 2015). Besides that local governments, research institutions and NGOs, should promote efforts and of working in synergy to produce relevant information with the aim of ensuring the implementation of public environmental policies and thereby improving land use (Arvor et al. 2021).

1.1. Rio de Janeiro State overview

Rio de Janeiro is among the states that has specific monitoring protocol and regulatory standards applied to offsetting and the PRA program. By comparing characteristics of the restoration areas in Rio de Janeiro, our results indicated varied results as presented on Table 1.

Table 1. Comparison of forest restorable areas in hectares on CAR and environmental offsetting programs in Rio de Janeiro State

Parameter	CAR	Offsetting
Avg size (ha)	5.51	4.03
Total area (ha)	340.106,48	6.636
SD (ha)	15.47	12.71

The average size of the forest restoration areas used in environmental offsetting is 4.03 ha (SD= 12.71), and on the average size in CAR is 2.46 ha (SD= 15.42).

The average size of forest restoration areas has direct implications for farmers' land use. In the light of the fiscal modules (FMs) which roughly mean the area enough for a family to have income, survive, and thrive is a concept brought by the Native Vegetation Protection Law (Law 12.651/2012) and gives equal treatment to all people who own up to four FMs through the Environmental Regularization Program (PRA) for small properties and family agriculture. Oliveira et al. (2020) used a case study in the state of Rio de Janeiro to analyze how updating the FM affects the PRA proposed by the Native Vegetation Protection Law and found that the existing FM groups in the state, which range from 5 to 35 ha.

The total area in the process of implementation or with a legal commitment to offset is 6.636 ha o and the total area that the CAR stipulates needs to be restored is 340.106.48 ha, divided between 286.275.24 ha for RL and 53.831.24 ha for APP.

This difference in the average size of the polygons can be explained because of the recovery of the APP varies depending on the size of the rural property, according to article 61-A of Federal Law nº 12.651/2012. The LPVN determines that the restoration projects can be done in a strip starting from 5 meters wide up to 100 meters along streams, springs, and rivers.

It is relevant to consider that that 53% of Brazil's native vegetation occurs on private properties which represent around 105 ± 21 GtCO2e (billion tons of CO2 equivalents) and play a vital role in maintaining a broad range of ecosystem services, so management of these private landscapes is critical if global efforts to mitigate climate change are to succeed (Soares-Filho et al. 2014).

It is also important to state that the size of the restoration projects can compromise the long-term biodiversity goals. There appears a negative correlation on the project size and the success of restoration in terms of biodiversity (Crouzeilles et al., 2016).

This difference has implications on financing and on the forest landscape restoration approach (Schultz et al., 2012) and should be part of a longer-term policy shift emphasizing large-scale, collaborative, and adaptive planning. It should be considered when planning environmental policies because it can suggest an improvement of 7,7 % of the Rio de Janeiro State area with forest cover. Currently Rio de Janeiro has 30% covered by native forests (SOS Mata Atlântica, 2017). In this case, planting is one of the steps and guaranteeing the results through monitoring is essential.

Monitoring systems

The evaluation of the methods and indication of forest restoration techniques in 14 states showed an average of prediction of techniques of 4,85 (±2,75). The state of São Paulo is considered a trendsetter, with its normative instrument mentioning 8 different restoration methods prediction (RMP) followed by the Federal District (7) and Rio de Janeiro (7). It is important to mention that no restriction was found on any RS the use of any forest restoration technique.

In Rio de Janeiro, the State Environment Agency (INEA) is pioneering the application of protocols providing a new legal framework in restoration, focused on the ecological "results" of restoration, rather than simply assessing the extent of implementation (Albuquerque et al., 2021).

At this point, it is important to avoid complex measures such as ecosystem services, carbon sequestration or biodiversity and ecosystem functionality (Tilman et al., 2014) due to the lack of qualified staff for monitoring forest restoration initiatives or even the costs involved on the data survey. Moreover part of the success of large-scale restoration is related to the development of restoration governance, communication, and articulation, promotion of strategies to influence public policies, and establishment of restoration monitoring systems (Crouzeilles et al., 2019).

The results indicate that only four states have established monitoring protocols in place though the use of remote sensing for monitoring is being analyzed in seven states (26% of total).

Two states, Acre (AC) and Federal District (DF), are developing auto-monitoring systems for the PRA, and its implementation is to be conducted by the respective landowners, that will simplify and turn more accessible the monitoring practice.

Communication is essentialand a good example is the Rio de Janeiro Forest Service (GESEF), which regularly promotes meetings and workshops to keep stakeholders informed and trained on the monitoring protocols and legal instruments of the local legislation, creating a channel to receive feedback from the system's users.

The GESEF experience reveals that the acceptance and compliance with the regulations on forest restoration is higher when the stakeholders are involved (Moura et al., 2019). The sustainability and adherence to the legislation should be based on the three pillars: feasibility, desirability and liability of application of the established laws.

Conclusions

The practice and management of forest restoration and its monitoring, still a novelty for governments and environmental agencies. The uprising of specific regulatory standards for forest restoration indicates that and may enhance restoration effectiveness by clarifying the restoration process and rules to all stakeholders involved in implementing projects. The Federal Decree nº 7.830 in 2012 which regulates the Environmental Rural Registry (CAR) led to the emergence of state regulations, aimed at organizing environmental regularization initiatives on rural properties. In addition to regulatory standards and policy instruments, monitoring still incipient, and few regulatory standards predicted the activity. However, states must conduct their restoration asset surveys in order to develop environmental policies and strategic planning that can generate multiple environmental and socio-economic thereby meeting international restoration commitments.

The state of Rio de Janeiro can be considered a reference model since it gone beyond the regulatory standards, but created a forest restoration management system, ensuring access to information, transparency, and effectiveness in communicating and monitoring environmental commitments.

Finally, it is necessary that the public authorities organize, prepare and create mechanisms that facilitate the new reality that arises from environmental adequacy in rural properties throughout Brazil. When implemented, forest restoration can guarantee and maximize the social and environmental benefits resulting from this activity.

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RESEARCH ARTICLE

A novel monitoring protocol to evaluate large-scale forest restoration projects in the tropics

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Abstract
The purpose of this paper is to present a proposal of forest monitoring and an evaluation system adjusted for tropical forest restoration initiatives in support of decision-making, tracking and management in an offsetting policy context. This study is framed by the case study of the Rio de Janeiro State Environmental Agency (INEA RJ) in Southeastern Brazil. We tested a set of indicators to evaluate restoration projects up to 4 years since planting. After the data were collected, we developed a scorecard and tested it in the field, allowing the evaluation of project development on a scale from 0 to 10. This analysis indicates conformity or a need for adequacy. We measured 7853 individuals on 205 sample plots. The projects had an average age of 32 months in the range of 14–48 months. The average scorecard value was 5.87 points, and we adequately assessed ecosystem structure, composition, function, species composition and organization. We create an evaluation tool to support decision-makers as also the restoration practitioners' decisions. The main innovation was to popularize the forest monitoring among stakeholders independent of the technician's experience background, by offering a simple, accessible, and robust protocol.

Keywords Ecological indicators · Forest restoration · Monitoring protocol

Introduction

Forest restoration is one of the most effective strategies to prevent biodiversity loss (Ditt et al. 2010; Bullock et al. 2011) and an important method for in situ biodiversity conservation. To accomplish biodiversity conservation goals (Myers et al. 2000), climate change agreements and ambitious international commitments to implement forest and landscape restoration (FLR) are needed, along with political awareness and financial mobilization (Brancalion and Chazdon 2017). However, to ensure the quality of forest restoration efforts, monitoring and evaluation should be part of the project and program routines to manage and verify results and accomplishment (de Souza and Batista 2004; DeLuca et al. 2010).

The effectiveness of forest restoration in human-dominated landscapes, such as the Brazilian Atlantic Forest biome, where at least 70% of the Brazilian population live (Metzger 2009) with high dependence on ecosystem services need to be monitored and evaluated in order to guarantee the biome conservation, the supply of water, food production, among others services provided by forests (Benayas et al. 2009; Calmon et al. 2011). Assessing the success of forest restoration projects is critical to select best practices and strategies to promote natural resource management (Wortley et al. 2013). Of similar importance is the determination and evaluation of the risks assumed in forest restoration projects, especially regarding poor control and measurability, long time lags and unpredictable scenarios (Maron et al. 2012).

Therefore, an adequate monitoring system is essential to support decision-making and to follow-up the results of restoration (Nilsson et al. 2016). In addition, strategic comparison with reference sites is crucial during evaluation (Lawley et al. 2016). However, it is usually not feasible to directly monitor all important forest attributes and functions, making it necessary to select a few indicators (Burton 2014).

Moreover, all indicators must represent current conditions and be responsive to guide the management of the

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restoration project. They must also be robust enough to evaluate an area independently of the technique used to start the restoration process. Also, the indicators should be integrative and allow the decision-maker to infer about the ecological trajectory and ecosystem functioning.

The International Society for Ecological Restoration has established nine ecosystem attributes that can be used as guidelines for assessing the success of restoration (Clewell et al. 2004). The Society of Ecological Restoration (SER) has suggested: similar diversity and community structure in comparison with reference sites; the presence of indigenous species; the presence of functional groups necessary for long-term stability; the capacity of the physical environment to sustain reproducing populations; normal functioning; integration with the landscape; elimination of potential threats; resilience to natural disturbances; self-sustainability.

Although measuring these attributes could provide an excellent assessment of restoration successes, few studies have the financial resources to monitor all these attributes. Furthermore, estimates of many attributes often require detailed long-term studies, but the monitoring phase of most restoration projects rarely surpass more than 5 years (Ruiz-Jaen and Aide 2005).

It is relevant to consider that the results of forest restoration nowadays are in the Anthropocene context (Coombs 2014), which is diametrically different from an idealized, pristine forest (Stanturf et al. 2014). In this sense, most tropical forests are becoming altered ecosystems, in which the degree of alteration depends on the intensity and duration of human-induced pressures (Malhi et al. 2014). Therefore, it is necessary to distinguish different types of reforestation stands based on their origins, dynamic properties and landscape settings (Chazdon et al. 2016), and the monitoring system should consider these differences and be goal-oriented (Noss 1999).

Currently, the effectiveness of restoration programs promoted in Latin America relies on their integration with national and subnational restoration frameworks and organizations, which can be supported by restoration networks (Meli et al. 2017). At the same time, large-scale forest restoration faces challenges such as how to prove its ecological effectiveness, the absence of tools to support decision-making processes and other factors (Brancalion and Chazdon 2017). The decision-making process needs the support of tools and frameworks that should be integrated with public policies aimed to promote and guarantee forest restoration (Durigan et al. 2010; Assis et al. 2013), providing clear rules that can be more effective than financial incentives for forest restoration.

This work aims to present and analyze the ecological indicators used in a monitoring protocol applied in the evaluation of forest restoration projects at the Rio de Janeiro State Environmental Agency (Instituto Estadual do Ambiente, INEA-RJ) in Southeastern Brazil. The protocol was developed as part of the first State System for Monitoring and Evaluation of the Forest Restoration (SSMER). We tested the correlations among indicators and their performance in Atlantic Forest local conditions to evaluate the restored areas along the first years following the implementation.

Materials and methods

Site description

The state of Rio de Janeiro (Brazil) is located in the Atlantic Forest biome, an evergreen humid tropical forest along the Atlantic coast and inland semi-deciduous forests (Joly et al. 1991). With elevations ranging from 0 to 1700 m above sea level, the climate is tropical (hot and humid), with temperatures varying between 20 and 27 ºC. The hottest months are between November and April and the coldest between May and October. Rain is most frequent between December and March, with January being the wettest month. The driest period runs from June to September. In summer, the temperature can reach 40 ºC, and in winter nights, it can drop to 15 ºC (Dubreuil et al. 2018).

The 4,377,783 hectares of the state of Rio de Janeiro were originally 100% covered by the Atlantic Forest. Nowadays, the state has 18.7% of its area covered by forests in good condition or in natural regeneration (SOS Mata Atlântica 2018), and 14,566 hectares to be restored under offsetting compromises derived from environmental licensing regulations accordingly the Rio de Janeiro State Forest Service.

Data collection

We selected 34 restoration projects across the state of Rio de Janeiro, focusing on the phytophysiognomy of the evergreen forest. We evaluated each project using selected indicators (Table 1) to create a benchmark of reference parameters for restoration projects. In each project, sampling plots were installed according to the intensity defined by the monitoring protocol for the Atlantic Forest Restoration Pact (AFRP) (Viani et al. 2013): Si = (PA-1) + 5, where: Si = sample intensity; PA = project area (ha). The sampling intensity formula indicates the number of plots to be monitored in each project area up to a maximum of 50 plots per project area.

Each plot was geo-referenced and had a fixed area of 100 m^2 (25 × 4 m), outlined by measuring tape facing the magnetic north. Sampling plots were distributed systematically at least 50 m from each other to encompass the heterogeneity of the vegetation in each area. Due to similarities with installing plots on soil sampling methods that are undertaken to provide average values of soil nutrient properties across

Table 1 Defined indicators of the protocol for forest monitoring

Indicator	Unit	Description
Density of individuals	Individuals per hectare	Counted individuals ≥ 0.6 m height
Zoochory	Percentage of the total spp.	Identified syndrome of all counted individuals according to the literature review
Canopy cover	Coverage percentage	Measured coverage that touches the measuring tape at the center of the plots
Evenness	J'	Refers to how close in number each species is in an environment
Richness	S'	Identified species according to the literature review
Height	Average of individuals	Measured height of all individuals ≥ 0.6 m inside the plots
Alien grass cover	Coverage percentage	Measured coverage that touches the measuring tape at the center of the plots

a field (Pennock et al. 2007), we used the same principles to sample the vegetation in each area.

The sampling procedure considered: division of the project area in homogenous stands; assurance of sampling different forest stands in terms of development (if applicable); division of the topographic portions of the terrain, such as lowlands, slopes, and hilltops. In the field, technicians collected the raw data in a spreadsheet. For each tree individual inside the plots, the species was identified, and the height and canopy cover were measured. For the measurement of height, we used a 2-m graduated stick, and for the canopy cover, we used a 30 m measuring tape. Inside the sampling plot, every individual higher than 0.6 m was identified and counted to determine the density of individuals.

We measured the linear projection of the canopy cover in an overlap over the measuring tape laid on the ground. The same procedure was applied for measuring the alien grass cover, where every grass clump touching the measuring tape was accounted. We considered a species as alien when its original occurrence was outside the Atlantic Forest.

Selection of indicators

The indicators were based on the benchmark suggested by the Atlantic Forest Restoration Pact (AFRP) (Viani et al. 2013) and by the Society of Ecological Restoration (SER)—International Primer on Ecological Restoration (Clewell et al. 2004). The selection of indicators is in accordance with what is recommended by Vallauri et al. (2005), in a multiple-criteria set using the SMARRT approach: Simple [e.g. vegetation cover (%), number of tree species present]; Measurable (e.g. biodiversity indices, indices of productivity for timber and nontimber products and money flow for restoration and monitoring); Reliable (e.g. ecological function demonstrated, indicators of structure and composition); Relevant: It should be linked, if possible, to critical stage(s) of ecosystem change in response to restoration or other management (the notion of ecological thresholds; e.g. criteria expressing or reflecting biodiversity, flows and functions, structure and contingency); Timely: Indicators should be chosen taking into account the contingency factors imposed by previous uses and degradation as well as the restoration process and their responses should be measurable on the lifetime of the project. The framework for monitoring should be ideally developed starting with an initial evaluation prior to the project and thereafter be reassessed regularly. The periodicity of the evaluation needs to be in accordance with the planned process of restoration, taking into account goals, phases and stages of the entire project.

To evaluate the restoration projects up to 4 years after planting, we tested the following indicators: (1) density of individuals; (2) percentage of zoochoric species; (3) canopy cover; (4) evenness; (5) species richness; (6) average height of the trees; and (7) percentage of alien grass cover (Table 1).

We choose variables that allow monitoring of the project performance at any age or stage and selected projects with ages of three and/or four years. According to the State Environmental Agency (INEA) regulations, 4 years is the minimum period to accomplish the restoration goals of the projects. The indicators were separated into three assessment outcomes: critical, minimum, or adequate which have a score associated; 0 (zero) for critical, 0.65 for minimum, and 1.0 for adequate.

The density of individuals (individuals/hectare) the threshold of 1111 individuals per hectare was obtained by calculating the number of individuals planted in a wider spacement accepted by the State Forest Service, which is 3 × 3 m scheme and represents that each individual occupies a 9 m^2 area (Moura et al. 2019).

Percentage of zoochoric species—animal-mediated seed dispersal is an important mechanism of propagule dissemination in tropical forests, where a vast proportion of the woody plant species are dispersed by vertebrates rather than wind, water or other abiotic processes. In general, fragments of Atlantic Forest have at least 80% of the woody plant species of the regional flora dispersed by animals (Tabarelli and Peres 2002). To be conservative, we considered that a minimum of 40% of the local pool of species should be dispersed by animals, and an adequate restoration project should have more than 60% of the species being animal-dispersed 4 years after planting (Fleming et al. 1987; Tiffney and Mazer 1995; Moles and Westoby 2006).

Canopy cover—this represents the area of ground covered by a vertical projection of the canopy (Jennings et al. 1999; Korhonen et al. 2006). The coverage indices in the Brazilian Atlantic Forest can be greater than 90% in a late-successional forest (Bianchini et al. 2003), and because of the inherent characteristics of a plantation, we consider as 50% the minimum accepted and adequate higher than 70%.

Evenness (J´)—parametrization was based on lack of dominance (or the complementary term, evenness); for this study, we consider the reference range of J´ as minimum of 0.6 and adequate as 0.8. Our decision was based on data obtained by Souza and Batista (2004) for areas of Atlantic Forest who found an evenness indexes for similar areas of AF with 5 years (J = 0.66) and 9 years (J = 0.71), and 10-year-old area (J = 0.84).

Species richness (S´)—considering a succession-based model which consists of ‘filling’ and ‘diversity’ planting lines proposed by Rodrigues et al. (2009), which uses 15–30 fast-growing species that are planted to promote fast soil coverage and improve environmental conditions near the ground. We consider 15 species as the minimum accepted and 25 or more species as adequate.

Average height (m)—we consider the results presented by Campoe et al. (2014), who found an average height of 1.6–3.0 m for an Atlantic Forest restoration experiment using tree planting as a restoration strategy. We consider an average size of 2 m in height as the minimum accepted and an average higher than 3 m as adequate.

Alien grasses cover (%)—this represents the area of the ground covered by alien grasses. For restoration goals, we considered 30% as the minimum accepted and as adequate less than 20% of the ground covered by grasses.

Data analysis

We calculated the density of individuals, the percentage of zoochoric species, canopy cover, evenness, species richness, average height and alien grass cover, following the procedures described in Viani et al (2013).

The density of individuals was determined based on individuals' ≥ 0.6 m in height, counted inside each plot of 100 m^2 and then extrapolated to individuals per hectare. The percentage of zoochory was determined by the calculation of the percentage of the total number of individuals from zoochoric species when compared to the other types of dispersal strategies.

Canopy cover and grass cover were the percentages of the ground covered by canopy projections or grasses inside each plot, following the formula: $(Lp1 + Lp2 + \ldots Lpn)*100/LT$; where Lp(n) is a projection of canopy or grass that touches the tape positioned in the centre of the sample plot (see Fig. 1) and LT is the linear size of the sampling plot in meters.

Pielou's evenness index (J´) is a measure of biodiversity and quantifies how equal the community is numerically; it is constrained between 0 and 1. The lowest evenness values indicate the presence of a dominant species in a community, while higher values indicate a community without a dominant species.

To determine the richness of species (S), we identified the species to the lowest taxonomic level, in the field or according to the literature.

Average height was calculated considering the arithmetic mean of the measured individuals of the project evaluated.

To allow the evaluation of the restoration projects, we developed a scorecard with the variables to be measured in the field; scores ranged from 0 to 10 (Table 2).

The scorecard can be easily understood and standardizes the evaluations made by technicians from diverse professional backgrounds. In this sense, due to the demand for the evaluation of restoration projects of the Rio de Janeiro Forest Service, we consider a threshold score that indicates the approval of the project if it reaches the total value of 8.0 or indicates a need for adequacy if the final score is below 8.0.

We used Pearson´s correlation coefficient to measure the strength and direction of the relationship between the variables calculated, applying Action Stat plugging in Microsoft Excel.

Results

The 34 studied projects had an average age of 49 (± 15) months since planting. The total sampled area covered approximately 1000 hectares, distributed in nine watersheds across the state of Rio de Janeiro. We identified 417 tree species from 140 botanical families and measured 20,320 individuals on 915 sample plots.

The average score was 6.6 (± 2). Using the scorecard, it was possible to assess the ecosystem structure, composition, function and species composition (Fig. 1).

The average values of the 34 evaluated projects were 2221 individuals per hectare, 55% of zoochory species, 50% of canopy cover, 0.82 of evenness, 57 of species richness, 2.2 m of average tree height, and 56.1% of alien grasses cover.

The evaluation of each indicator and its adjustment was, on average, 51.5%, reaching the expected range of performance for projects until 4 years since planting (Table 2). The indicators that performed well were tree density (91.2%), evenness (100%) and richness (94.1%), which means that three out of seven indicators performed as expected.

There was a strong correlation among the indicators according to Pearson's correlations coefficients. We measured the degree of the linear relationship between each pair

DE	ZO	CC	EQ	RI	HE	GC	FS
38,52	34,00	0,69	68,00	1,81	100,00	38,52	3,7

DE	ZO	CC	EQ	RI	HE	GC	FS
1357,14	50,26	46,15	0,82	54	2,48	95,22	6,14

DE	ZO	CC	EQ	RI	HE	GC	FS
1211,00	45,28	61,6	0,79	68	3,1	57,1	7,57

DE	ZO	CC	EQ	RI	HE	GC	FS
2171,42	67,11	73,49	0,75	29,00	3,06	100,00	8,07

Fig. 1 Visual comparison of protocol scores

Table 2 Proposed indicators and reference parameters for the Atlantic Forest in Rio de Janeiro—Brazil

Project evaluation / forest (year 4)			
Indicator	Critical = 0	Minimum = 0.65	Adequate = 1
Density (ind/ha)	< 1111	> 1111 < 1250	> 1250
Zoochory (%)	< 40	≥ 40 < 60	> 60
Canopy cover (%)	< 50	≥ 50 < 70	≥ 70
Evenness J’	< 0.6	≥ 0.6 < 0.8	> 0.8
Richness S'	< 10	≥ 10 < 20	≥ 20
Height (m)	< 2.0	≥ 2.0 < 3.0	> 3.0
Grass cover (%)	> 30	> 20 < 30	< 20
Final score		$\sum p \times \frac{10}{np}$	

of our variables and found a strong correlation (r(34) = 0.94 P < 0.001) (see Table 3).

Discussion

We tested indicators and evaluated restoration projects in the state of Rio de Janeiro and our results indicate that the chosen indicators are representative and support the approach of using a single index as a final score for evaluating projects of evergreen and semi-deciduous seasonal forests.

Considering our results, the average time since planting was 49 (± 15) months. According to the Inea Resolution 143/2017, the projects can be considered accomplished only after 48 months and when they reach a minimum of eight in the scorecard evaluation. However, the average score was

Table 3 Correlation matrix of the indicators used in forest monitoring in the state of Rio de Janeiro, Brazil

Correlation matrix							
	DE	ZO	CC	EV	RI	AH	GC
DE	1	0.96965757	0.94460718	0.92186608	0.97733238	0.91450216	0.91772249
ZO	0.96965757	1	0.92210367	0.91347204	0.98574055	0.88229809	0.89358566
CC	0.94460718	0.92210367	1	0.94228246	0.94808144	0.98471609	0.95175899
EV	0.92186608	0.91347204	0.94228246	1	0.92206006	0.95246584	0.88561381
RI	0.97733238	0.98574055	0.94808144	0.92206006	1	0.90866576	0.90650774
AH	0.91450216	0.88229809	0.98471609	0.95246584	0.90866576	1	0.9427836
GC	0.91772249	0.89358566	0.95175899	0.88561381	0.90650774	0.9427836	1
P-value matrix							
	DE	ZO	CC	EV	RI	AH	GC
DE	1	3.8159E–21	4.8502E–17	1.0094E–14	3.794E–23	4.0411E–14	2.2386E–14
ZO	3.8159E–21	1	9.631E–15	4.8577E–14	2.4224E–26	5.3008E–12	1.1488E–12
CC	4.8502E–17	9.631E–15	1	9.207E–17	1.7643E–17	7.2978E–26	5.5925E–18
EV	1.0094E–14	4.8577E–14	9.207E–17	1	9.7145E–15	4.4387E–18	3.4395E–12
RI	3.794E–23	2.4224E–26	1.7643E–17	9.7145E–15	1	1.1136E–13	1.5926E–13
AH	4.0411E–14	5.3008E–12	7.2978E–26	4.4387E–18	1.1136E–13	1	8.037E–17
GC	2.2386E–14	1.1488E–12	5.5925E–18	3.4395E–12	1.5926E–13	8.037E–17	1

DE density of individuals, *ZO* zoochory, *CC* canopy cover, *EV* evenness, *RI* richness, *AH* average height, *GC* grass cover

6.6, indicating that the projects did not meet the requirements. In light of Resolution 143, these projects would be disapproved for not achieving the expected performance at the age of 4 years of planting. In these cases, the person committed to the project must promote actions that ensure the progress of the indicators in reaching the minimum pass mark. These results bring new data on forest restoration in Rio de Janeiro, indicating that ongoing projects have low quality when evaluated using silvicultural and ecological performance indicators.

The average density found by this study was 2221 individuals per hectare in the first 4 years of development, our value is higher than that found by Londe et al. (2020) for reference values in a broadleaf rainforest. It is important to consider 83% of the restoration projects in the State of Rio de Janeiro use the total area planting method, on the spacing of 3 × 2 m, which results in 1667 trees per hectare (Moura et al. 2019). In this sense, densities above 1667 ind./ha indicate the arrival and establishment of natural regeneration which therefore implies the reestablishment of an important ecological functionality towards the long-term sustainability of the restoration.

We provide a synthesis as a set of categorical ratings in order to determine the responses of the ecological restoration attempt to the local environment and site conditions corroborating with Parrish et al. (2003) creating what they called "Measures of Success".

Considering the chosen indicators, we found it applicable, understandable, economical, and time-efficient, and easy to obtain the data in the field, even for non-specialized technicians.

The density of individuals can easily be obtained and is a comprehensive parameter, and should be more than counting the number of dead or alive seedlings, but the focus should measure the establishment of a minimum density of trees expected for a forest ecosystem. So, the arrival of seeds and their expression on the form of natural regeneration can provide the planner by comparison with what was planted on the implementation of the project and the list of species of the project. By this, the monitoring results can indicate features of ecosystem functioning advancing in the direction of the approach of biodiversity and ecosystem functioning (BEF), including an evaluation of ecosystem services provided by those initiatives (Brose and Hillebrand 2016).

Regarding the percentage of zoochory species, the measurement of this indicator is labor and time intensive and requires a professional with skills in botany and ecology, to classifying each species and its associated dispersal syndrome. Despite that, it is important to evaluate this parameter as it indicates the availability of resources for animals in the project as potential dispersers, which can contribute to the sustainability of the restoration stand in the medium and long term.

The average result for canopy coverage was 50.13%, and it did not reach the adequate level required by Resolution 143, which is 70% coverage. The importance of this indicator is due to the fact that one of the main degradation factors in reforestation, and therefore the arrestment of the succession (Kellerman and Lacerda 2019), is linked to the occurrence of invasive exotic grasses that hinder the establishment of natural regeneration, compete for nutrients, and are an important fuel to the fire.

Regarding the measurement of evenness (J´), our results indicated that projects meet this parameter with ease. The average value found for J´ was 0.82 while Resolution 143 requires 0.8 as adequate. This indicates that the plantations respect the expected patterns for the tropical forest, regarding the pattern of distribution of individuals among the species, being proportional to the diversity; such patterns are important in highly diverse tropical forests. However, the use of J´ as an ecological index requires a professional familiar with botanical and forest ecology. It should be borne in mind that this indicator requires more attention, as it can be a source of methodological bias.

About species richness, this proved to be an appropriate measure to infer on the diversity of the plantation. Not using indices such as Shannon Weaver makes it easier to obtain and can be easily obtained by identifying even morph-species. Thus, we consider that an affordable parameter is more operational on a large scale and therefore can reduce restoration costs. The same can be applied to medium height and strange grass cover. This was also a parameter that the projects were able to meet with ease, whose average value was 57, while the current regulation requires 25.

Although only three out of seven indicators should accuracy of over 80%, this does not mean that the indicators were not adjusted; it rather suggests poor outcomes of the restoration projects. Only 23% of the projects reach the 8.0 score and didn't attend to the minimum standard as acceptable to approval. In this sense, it is important to have a rigorous evaluation system in place to guarantee the minimum of ecological functioning and sustainability.

This study also showed some weaknesses in its methodology, such as not directly or indirectly considering the strata of the new forest. It also did not measure any life forms other than trees. Further studies, including socio-environmental parameters, are needed. Advances in the proposed protocol will be made over time, making it more accessible and easier to use, especially for non-academic users. It is also important to consider that a monitoring protocol should combine, if possible, the ecological, socioeconomic and project management dimensions of forest restoration (Viani et al. 2013).

Our results indicate that the use of indices for monitoring, can be accessible and used on a large scale, and can be considered useful and robust for evaluating tropical reforestation projects. The definition of clear and pre-established rules as a public policy generating reference values and an accessible protocol was well accepted by the stakeholders.

The parameters used by Resolution 143 are sensitive to changes over the time of the project and allow inferences about the ecological trajectory, evaluating the structure, composition and functioning of the recovered forest.

Monitoring and evaluation should start just after the implementation of the restoration project to adjust and make corrections, if needed, as soon as possible. In the case of Atlantic Forest in the state of Rio de Janeiro, monitoring should be performed once a year because the variables slowly change in a period of time shorter.

It should be mentioned that even with the use of protocols and clear rules, monitoring has a certain degree of bias. To increase the precision with a larger dataset, a more complex analysis should be conducted and new ranges of acceptance by Resolution 143 should be settled, as new indicators can be included or excluded. Thus, with more sites monitored, comparisons considering a landscape level can be useful in the evolution of this protocol (Vallauri et al. 2005).

This work provides a benchmark for the state of Rio de Janeiro, originally covered by the Atlantic Forest and a biodiversity hotspot, synergistic with the Brazilian goal at the COP 21 in Paris, serving as a tool to assess actions in response to climate change. The proposed protocol is already incorporated in the State Environmental Policy as a subnational standard.

Conclusions

Monitoring is now a part of the projects outlined in the Rio de Janeiro State Environmental Policy as an essential step in assessing the accomplishments of a restoration process through evaluation of the results, not the methods used. It corroborates with the AFRP statement, in which forest restoration activities would be incomplete without subsequent feedback. The adopted scorecard can be considered as a naturalness index of the forest at a landscape scale under restoration in early years, which we named the "implementation phase".

Our results indicate that the used protocol is appropriate as a decision-making tool. The protocol enables managers to monitor results and to empirically provide directives and recommendations to start adaptive management. It also offers solutions to improve the performance of each parameter and, subsequently, to increase the efficiency of ecological processes in restoration, with a direct impact on project costs.

The framework for monitoring forest restoration is now widely recognized by local stakeholders and should be reappraised regularly. The evaluation needs to be performed once a year for at least 4 years or until the score of 8.0 is reached.

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remote sensing

Article

Forest Restoration Monitoring Protocol with a Low-Cost Remotely Piloted Aircraft: Lessons Learned from a Case Study in the Brazilian Atlantic Forest

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Abstract: Traditional forest restoration (FR) monitoring methods employ spreadsheets and photos taken at the ground level. Since remotely piloted aircraft (RPA) generate a panoramic high resolution and georeferenced view of the entire area of interest, this technology has high potential to improve the traditional FR monitoring methods. This study evaluates how low-cost RPA data may contribute to FR monitoring of the Brazilian Atlantic Forest by the automatic remote measurement of Tree Density, Tree Height, Vegetation Cover (area covered by trees), and Grass Infestation. The point cloud data was processed to map the Tree Density, Tree Height, and Vegetation Cover parameters. The orthomosaic was used for a Random Forest classification that considered trees and grasses as a single land cover class. The Grass Infestation parameter was mapped by the difference between this land cover class (which considered trees and grasses) and the Vegetation Cover results (obtained by the point cloud data processing). Tree Density, Vegetation Cover, and Grass Infestation parameters presented F_scores of 0.92, 0.85, and 0.64, respectively. Tree Height accuracy was indicated by the Error Percentage considering the traditional fieldwork and the RPA results. The Error Percentage was equal to 0.13 and was considered accurate because it estimated a 13% shorter height for trees that averaged 1.93 m tall. Thus, this study showed that the FR structural parameters were accurately measured by the low-cost RPA, a technology that contributes to FR monitoring. Despite accurately measuring the structural parameters, this study reinforced the challenge of measuring the Biodiversity parameter via remote sensing because the classification of tree species was not possible. After all, the Brazilian Atlantic Forest is a biodiversity hotspot, and thus different species have similar spectral responses in the visible spectrum and similar geometric forms. Therefore, until improved automatic classification methods become available for tree species, traditional fieldwork remains necessary for a complete FR monitoring diagnostic.

Keywords: Atlantic Forest; drones; SfM-MVS; structural parameters; unmanned aerial vehicle

1. Introduction

Remotely piloted aircraft (RPA), popularly known as drones, present notable technical advantages in several fields, such as journalism [1] and agriculture [2]. Nevertheless, in Forest Restoration (FR) projects, the real benefits that RPA can provide still demand more studies.

Traditional FR monitoring methods employ sheets and photos taken at the ground level that do not register the whole area of an FR project, e.g., the methods described in the FR monitoring protocol of the Brazilian Atlantic Forest biome [3]. According to Viani et al. [4], the Atlantic Forest FR monitoring protocol is excellent because it provides data collection standards to avoid biases and subjectivity. As the scope of future studies, the authors stated that an automatic feedback report would improve the FR monitoring protocol. Therefore, it would be interesting to investigate whether RPA is capable of generating an automatic feedback report to efficiently support FR monitoring.

Since RPA generates a panoramic high resolution and georeferenced view of the entire area of interest [5], this technology has high potential to promote efficient FR monitoring [6]. Such potential demands studying how RPA can accurately and automatically provide the important FR monitoring parameters mentioned by McDonald et al. [7], such as tree cover, tree density, and tree species. In biomes like the Brazilian Atlantic Forest, which is a biodiversity hotspot [8], improving the FR monitoring protocol would help managing the targets stipulated under the Paris Agreement, wherein Brazil is committed to restoring 12 million hectares of forests by 2030.

This study aims to evaluate the manner in which RPA can contribute to the FR monitoring protocol of the Brazilian Atlantic Forest. Particularly, we evaluated a low-cost RPA [9] because financial resources are scarce in developing countries [10]. These findings play an important role in improving the FR monitoring protocol by considering an emerging remote sensing technology.

2. Materials and Methods

2.1. Study Area

The FR study area is located in the Brazilian Atlantic Forest biome, specifically at the Miguel Pereira Municipality in the state of Rio de Janeiro (RJ). Figure 1 illustrates this 23.45 hectare study area, where Instituto Terra de Preservação Ambiental (ITPA) conducted an FR project.

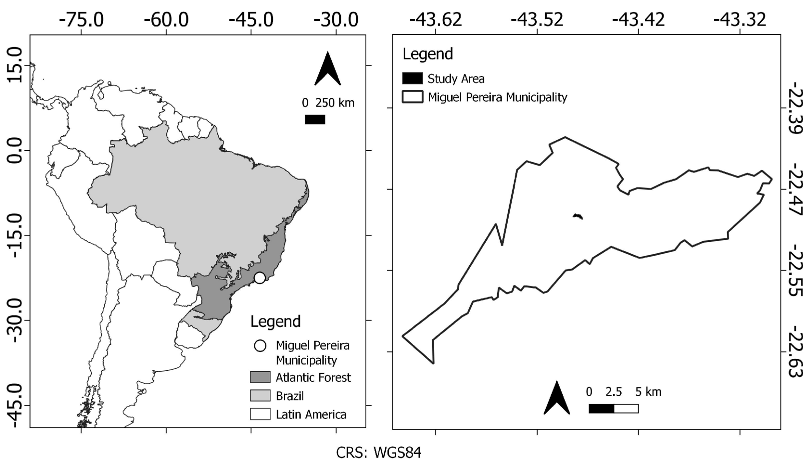

Figure 1. Location of the FR study area on Miguel Pereira municipality, situated in the Brazilian Atlantic Forest biome. To see the RPA orthomosaic and the study area on a greater scale, please go to Figure 3.

The traditional fieldwork with 19 field plots to officially monitor the FR occurred in October 2017. It followed the Fast Environmental Diagnosis Methodology [11], which is

Rio de Janeiro State's official FR monitoring process. In January 2018, the RPA fieldwork was conducted in the study area.

2.2. Materials

The RPA used in this study is a Phantom 4 Standard (a rotary wing). It is coupled with an RGB 1/2.3″ 12MP camera with FOV 94° 20 mm (35 mm format equivalent) lens, Electronic Shutter Speed of 8–1/8000 s, and Image Size of 4000 × 3000. More information regarding this RPA model can be found at https://www.dji.com/br/phantom-4, accessed on 26 May 2021.

The flight plan was drafted using the free software Pix4D Capture for smartphones/tablets. The Digital Surface Model (DSM) and orthorectified mosaic were obtained using the Agisoft Photoscan software. The classification processes and graph generation were performed using R [12] version 3.6 and the map layouts were generated using QGIS software version 3.12. The Cloud Compare software was used to generate the Digital Terrain Model (DTM).

2.3. Methods

2.3.1. Flight Patterns

Two flights were necessary to cover the entire study area. The flights were conducted in compliance with Brazil's RPAs laws [13] at a height of 80 m and generated an 8 cm Ground Sampling Distance (GSD). The front and side overlaps were equal to 80% to generate enough details in the point cloud data [14].

No Ground Control Points (GCPs) were collected by a geodetic Global Navigation Satellite System (GNSS) equipment, and thus the orthomosaic precision was around 3 m [15]. Such cartographic precision is considered enough for this study because change detection over time was not performed in this study [16].

2.3.2. Estimation of Forest Restoration Biodiversity Using Low-Cost RPA

Tree species were not distinguishable by photointerpretation on the RPA orthomosaic, as illustrated in Section 3. Thus, the estimation of the FR parameter Biodiversity by low-cost RPA was not considered in this study. Instead, this study focused on the FR structural parameters, which play an important role in FR monitoring [7]. The remotely measured FR structural parameters were Tree Density, Vegetation Cover, Tree Height, and Grass Infestation. Figure 2 shows the workflow for obtaining these FR structural parameters and the accuracy assessment. Sections 2.3.3–2.3.7 describe each step presented in Figure 2.

2.3.3. FR Structural Parameter: Tree Density

To estimate the Tree Density parameter, individual trees must be counted. Some studies have counted trees automatically using the Canopy Height Model (CHM) database [17], as the CHM is the difference between the DSM and the DTM [18]. In this work, the DTM was created by applying the Cloth Simulation Filter algorithm [19] in Cloud Compare software. Since the study area was sloping and contained some small trees, which were slightly higher than the grasses, these short trees were omitted in the DTM generation, and the CHM was consequently affected. Thus, the individual tree count was obtained directly from the DSM to increase automatic tree counting accuracy, as described in Albuquerque et al. [14].

The Local Maximum algorithm [20,21] of the rLiDAR R package [21] was used on the DSM to obtain the individual tree count. This algorithm searches for the highest value on a fixed window-sized kernel and generates a point table with geographic coordinates of the encountered maximum values. Individual tree count is then obtained by a coordinate set, where each coordinate represents the highest location of a tree crown.

To avoid the individual tree count commission errors (false-positives), two or more coordinates with a distance of less than 10 cm between them were excluded because they represent the same tree. Then, the geographic coordinates of the point halfway between these excluded points were retained to represent the tree. The ten-centimeter threshold value was defined because forest inventories consider only trees with trunk diameters of >5 cm [22], and thus trees must be at a distance of at least 10 cm from each other. More details about the individual tree count method applied in this work can be found in [14].

After the individual tree count was determined, the number of identified trees was divided by 23.45 hectares (size of the study area) to obtain the tree density.

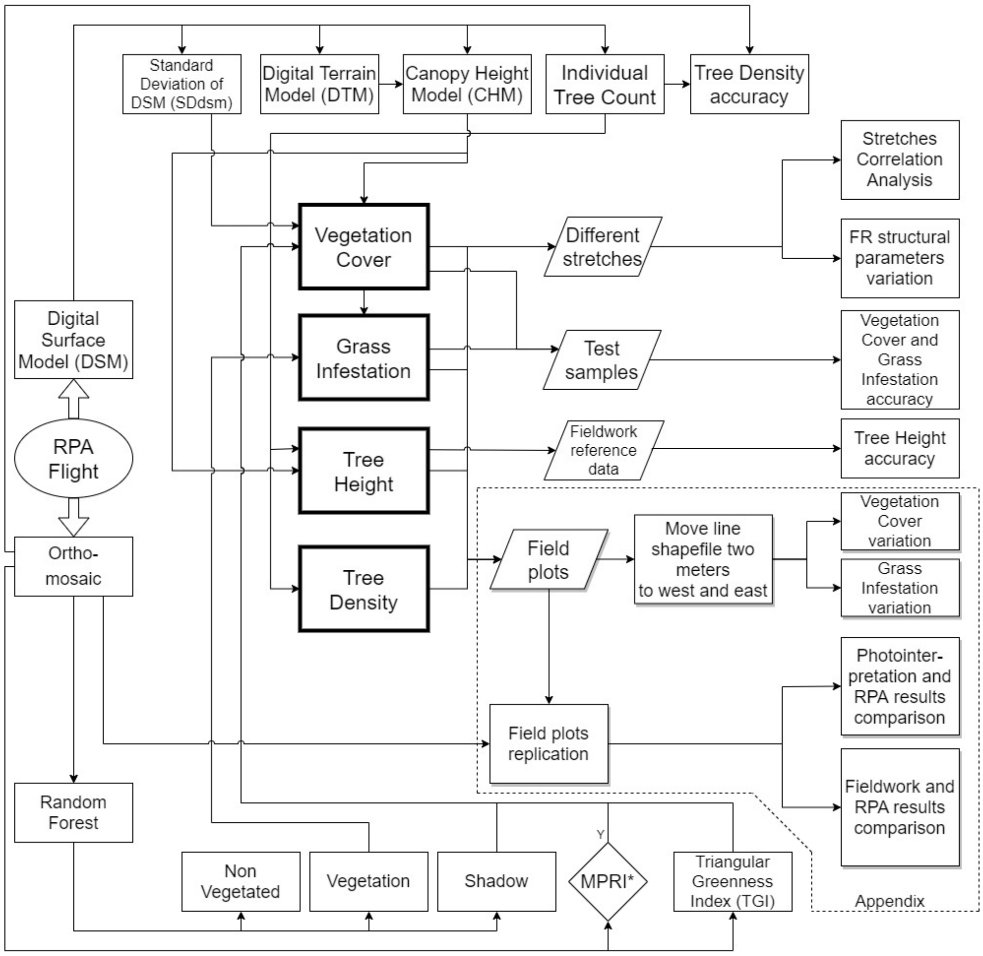

Figure 2. Methodology workflow of this study. MPRI is the Modified Photochemical Reflectance Index [23] and should be used only in the absence of shadow.

2.3.4. FR Structural Parameter: Tree Height

Tree height was determined in two steps: (1) extracting the CHM value corresponding to each geographic coordinate in the individual tree count; (2) calculating the mean of these extracted values. The height values were obtained from the individual tree count results as they correspond to the largest tree crown height value.

2.3.5. FR Structural Parameter: Vegetation Cover

To determine vegetation cover using RPA imagery, trees and grasses must be adequately distinguished. Vegetation cover involves the area covered by trees and not by grass, as Grass Infestation is a FR structural parameter described in Section 2.3.6. This study therefore considers that the variable vegetation is the sum of Vegetation Cover and Grass Infestation.

$$Vegetation = VegetationCover + GrassInfestation \quad (1)$$

Vegetation mapping was performed using a Random Forest supervised classification involving three land cover classes according to Reis et al. [24] and Laliberte et al. [25]: vegetation, shadow, and non-vegetated.

When using RPA to determine the vegetation cover, the CHM should involve only areas with trees, and therefore an accurate CHM would by itself provide the Vegetation Cover parameter. As explained in Section 2.3.3, trees that were slightly higher than grasses on sloping areas were excluded during CHM acquisition, and thus this database could not be used by itself to accurately obtain Vegetation Cover. To isolate Vegetation Cover, vegetation indexes like the Triangular Greenness Index (TGI) (Equation (2)) [26] can be an alternative.

$$TGI = [(Green - 0,39) * (Red - 0,61)] * Blue \tag{2}$$

TGI is not a normalized index, and vegetated areas tend to present negative values. In this work, the TGI could distinguish between trees and grasses, but it did not provide a final Vegetation Cover result on its own because some trees or some parts of tree crowns were missing, and thus the Standard Deviation of DSM (SDdsm) was also used for Vegetation Cover mapping.

The Standard Deviation of DSM (SDdsm) may be used to avoid confusion between trees and grasses because it has presented good results in detecting homogeneous topographic surfaces [27] and the arboreal stratum [28]. However, in medium-aged FR projects, like the one in this study, the height of trees varies considerably, and thus the application of SDdsm for vegetation cover mapping presents some limitations and should be used along with other variables.

Thus, the Vegetation Cover result acquired by RPA in this study was the sum of TGI Vegetated areas (TGIVeg), Standard Deviation of DSM (SDdsm), and CHM. As indicated by Equation (3), the sum of these variables for the Vegetation Cover mapping also involved the exclusion of shaded areas.

$$VegetationCover = [(TGIVeg + SDdsm + CHM) - (3 * Shadow) > 0] \tag{3}$$

Each variable in Equation (3) is a raster containing values equal to zero (means no occurrence) or one (means occurrence). Furthermore, in Equation (3), it is noteworthy that shaded areas, obtained by the land cover class Shadow, are multiplied by the number of layers containing vegetation areas. This ensures that areas mapped as vegetation by more than one vegetation layer will receive zero or negative values when they are overlapping with shaded areas. Moreover, if the values of the variables in Equation (3) are selected to be greater than zero, the equation can be solved using one line of computation code, instead of two.

Regarding the Modified Photochemical Reflectance Index (MPRI) [23], it did not contribute to Vegetation Cover mapping in this work because it generated a large amount of confusion with shaded areas.

2.3.6. FR Structural Parameter: Grass Infestation

In reality, Grass Infestation may overlap with Vegetation Cover because grass grows below a tree crown. However, Structure from Motion and Multi-View-Stereo [29,30], or SfM-MVS, is unable to record the surface below the tree crowns, and thus, in this study, it is considered that Grass Infestation does not overlap with Vegetation Cover.

Therefore, Grass Infestation mapping was conducted using Equation (1), which led to Equation (4) because Section 2.3.5 describes Vegetation and Vegetation Cover acquisition.

$$GrassInfestation = Vegetation - VegetationCover \tag{4}$$

2.3.7. Accuracy Evaluation

Remote measurements in environmental projects must be conservative, which means that overly optimistic results must be avoided [31]. Regarding the Grass Infestation structural parameter, as it is an undesirable variable in the Brazilian Atlantic Forest biome, an estimation containing more commission than omission errors is considered conservative. For Vegetation Cover, Tree Height, and Tree Density, which are desirable variables, the conservative path involves more omission than commission errors. In other words, FR classification results obtained using remote sensing must avoid commission errors in desirable FR structural parameters and avoid omission errors in undesirable FR structural parameters.

To estimate Tree Density in closed-canopy conditions, fieldwork may be necessary for acquiring reference data because the boundaries of the overlapping tree crowns may not be clearly identifiable by photointerpretation [32,33]. Since the canopy was not closed in the study area, a photointerpretation qualitative analysis [34] evaluated the accuracy of Tree Density. This qualitative analysis allowed the acquisition of omission and commission errors, or the amount of False-Positive (FP) and False-Negative (FN) occurrences, as well as the Overall Accuracy [35]. Recall, Precision, and F_score indexes [36] were then calculated according to Equations (5)–(7), respectively.

$$r = \frac{TP}{(TP + FN)} \tag{5}$$

$$p = \frac{TP}{(TP + FP)} \tag{6}$$

$$F_{score} = 2 * \frac{(r * p)}{(r + p)} \tag{7}$$

where: TP = True Positive, FN = False Negative, FP = False Positive, r = recall, p = precision.

Vegetation Cover and Grass Infestation accuracies were measured using a Confusion Matrix, along with Overall Accuracy, Producer's Accuracy, User's Accuracy, F_score, and Kappa Index. In total, 50 test samples were used for each of the three classes: Vegetation Cover, Grass Infestation, and Other Classes.

Tree Height is the only FR structural parameter in this study that cannot be evaluated by photointerpretation. Therefore, the accuracy of this parameter was measured using the Error Percentage [37] between the fieldwork and RPA results (Equation (8)).

$$ErrorPercentage = \frac{(Reference - Results)}{(Reference)} \tag{8}$$

2.3.8. Evaluating FR Structural Parameters Values in Stretches with Different FR Success

Since RPA can be used to map the entire project area, stretches with different vegetation singularities can be noticed [38]. In that case, stretches with more, less and intermediate FR success within the study area were manually separated by photointerpretation. The intermediate FR success stretches in this work were a mix of more and less FR successful areas. Figure 3 illustrates the polygons that represent these stretches.

A boxplot and correlation matrix quantitatively indicated if the different stretches in Figure 3 have different FR structural parameters. The boxplot illustrated how the FR structural parameters values vary between the final fieldwork results (the final fieldwork results can be found in Appendix A.3), as shown by Equation (9).

$$ErrorPercentage_{stretch} = \frac{(Fieldwork - RPA_{stretch})}{(Fieldwork)} \tag{9}$$

Thus, for each FR structural parameter, a boxplot graph was used to evaluate how the Error Percentage (Equation (9)) varied among the different FR stretches.

Furthermore, for example, to assess whether a high value of Vegetation Cover is associated with low values of Grass Infestation (it is expected that grass reduces as the canopy closes), a correlation matrix of the RPA results in the different stretches was evaluated.

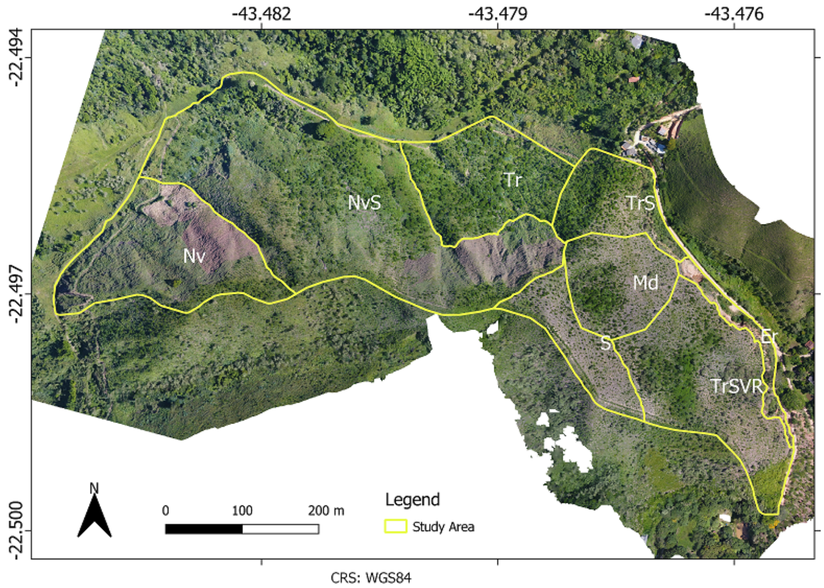

Figure 3. Study area divided into 8 different stretches with more, less, and mixed quantities of forested areas (FR success): Non-vegetated predominance (Nv), Non-vegetated mixed with Seedlings (NvS), Trees predominance (Tr), Trees mixed with Seedlings (TrS), Seedlings predominance (S), Trees mixed with Seedlings mixed with Vegetation Remnants (TrSVR), Erosions (Er) and Model (Md). The Md stretch was the one that best represented the whole study area in general.

3. Results

Regarding the Biodiversity parameter, it was not possible to identify tree species when replicating field plots in the RPA image. As shown in Figure 4, the study area has different tree species that presented similar spectral responses in the visible spectrum and similar geometric forms in the RPA image, which makes the classification process not possible because the human eye cannot state the difference [39]. Thus, traditional fieldwork will continue being necessary to record tree species in FR projects, and future studies should evaluate the performance of other types of sensors, such as multispectral and hyperspectral, in the estimation of Biodiversity.

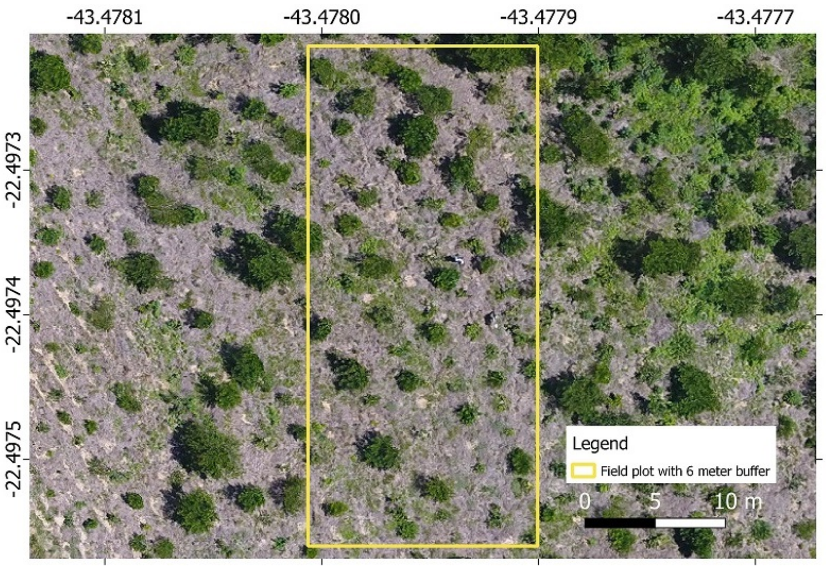

Figure 4. There are at least six different tree species in the rectangle area, but all of them are very similar, and none could be distinguished by photointerpretation.

Regarding the FR structural parameters, which were the focus of this study, Figures 5–7 show the RPA results in the whole study area. Figure 8 shows a zoomed-in version of the RPA results in the study area.

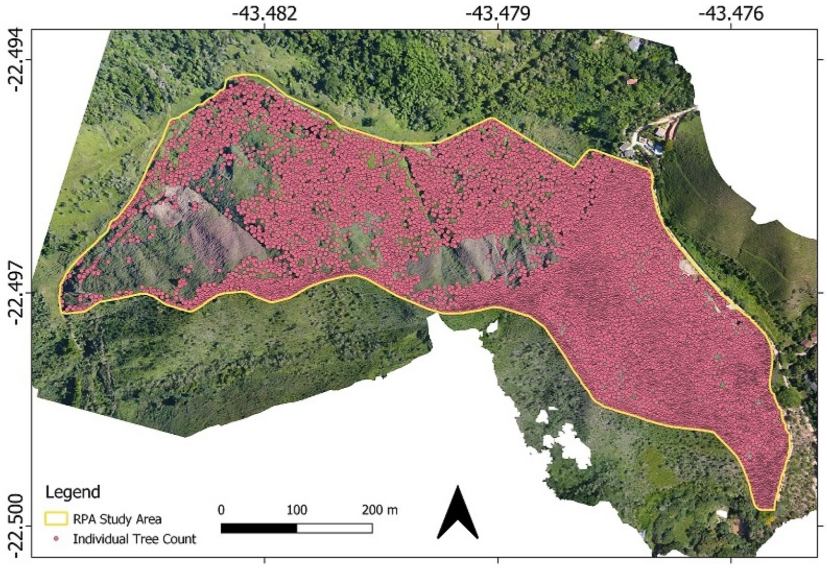

Figure 5. Individual Tree Count results of the RPA study area, which provided the Tree Density result when dividing all the identified trees by the area.

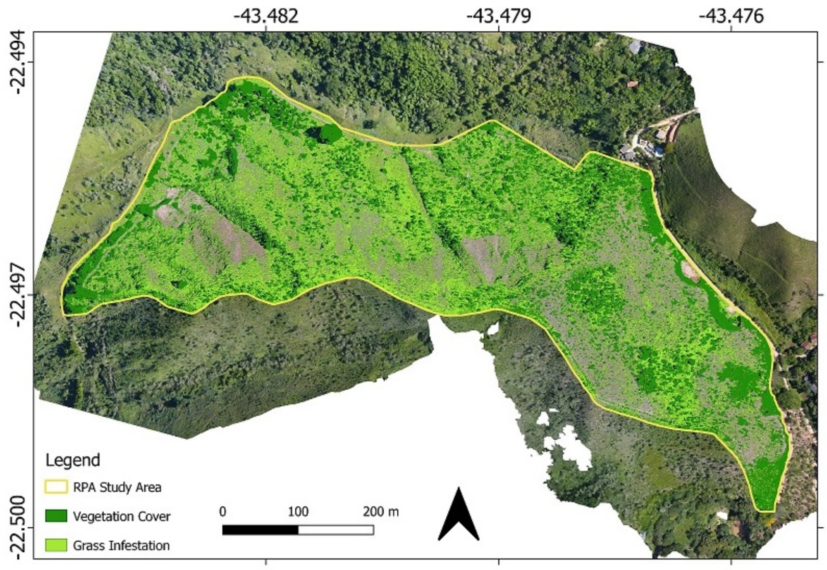

Figure 6. The Vegetation Cover and Grass Infestation results of the RPA study area.

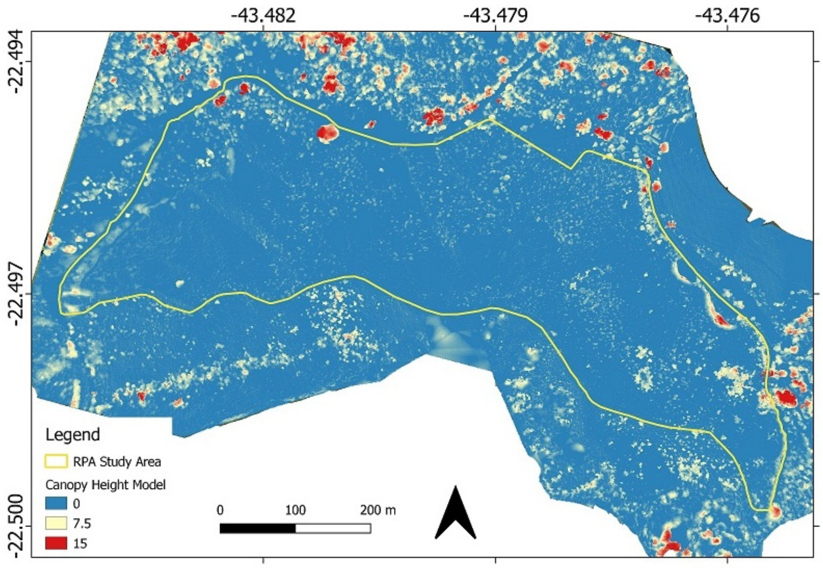

Figure 7. The Canopy Height Model (CHM) results of the RPA study area, which provided the height of the trees that were automatically identified. The zero CHM values mean grasses or non-vegetated (bare soil) areas.

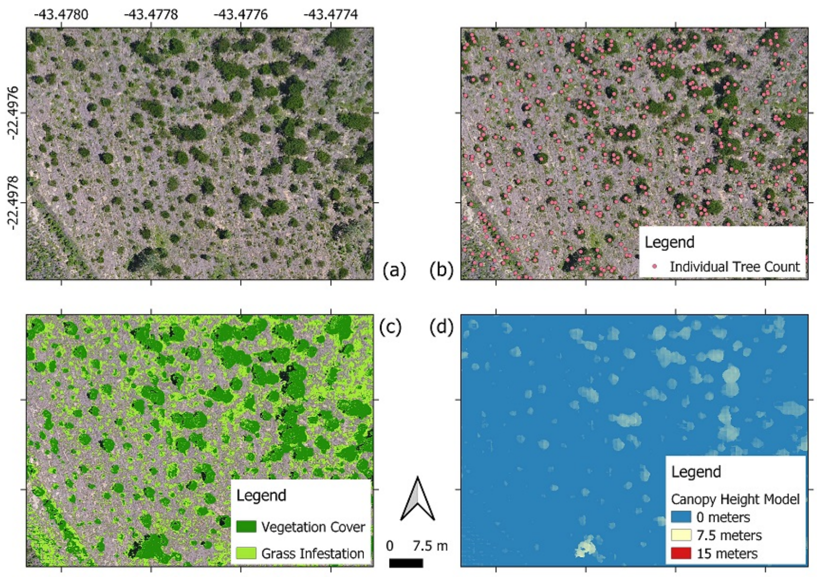

Figure 8. FR structural parameters results of the study area in a high mapping scale. (**a**) The RPA orthomosaic. (**b**) The Individual Tree Count, which provided the Tree Density result when dividing all the identified trees by the area. (**c**) The Vegetation Cover and Grass Infestation results. (**d**) The Canopy Height Model (CHM), which provided the height of the trees that were automatically identified and where zero CHM values means grasses or bare soil areas.

3.1. Vegetation Cover and Grass Infestation Accuracy

The Confusion Matrix shown in Table 1 presents high accuracy indexes for Vegetation Cover and medium accuracy indexes for Grass Infestation. The Overall Accuracy and the Kappa index of the Confusion Matrix are equal to 0.75 and 0.63, respectively. The F_score value was equal to 0.85 and 0.64 for Vegetation Cover and Grass Infestation, respectively. F_score ranges from 0 to 1 and has been widely used [14,17,32,33,40–44], and thus 0.85 and 0.64 can be considered high and medium accuracy values, respectively.

Table 1. Confusion Matrix for measuring Vegetation Cover (Trees) and Grass Infestation (Grass) accuracy.

		Target				
		Grass	**Trees**	**Other Classes**	**Producer's Accuracy**	**User's Accuracy**
Prediction	**Grass**	26 (52%)	5 (10%)	0 (0%)	52%	84%
	Trees	1 (2%)	41 (82%)	4 (8%)	82%	89%
	Other Classes	23 (46%)	4 (8%)	46 (92%)	92%	63%

3.2. Tree Density Accuracy

The Individual Tree Count method to obtain Tree Density presented Recall, Precision, F_score, and Overall Accuracy values equal to 0.93, 0.90, 0.92, and 0.87, respectively. These are considered high accuracy results. However, Individual Tree Count presented 10% of commission errors (undesirable for Tree Density), which may have influenced the achievement of accurate results because omission errors were compensated.

3.3. Tree Height Accuracy

The Tree Height value was equal to 1.68 m and 1.93 m when obtained using RPA and fieldwork (reference data), respectively. With such results, the Error Percentage was equal to 0.13, and thus Tree Height was accurate when measured by RPA because it is a conservative result that estimates a 13% shorter height for trees that are almost 2 m tall.

3.4. FR Structural Parameters Values in Stretches with Different FR Success

The stretches with different FR success, described in Section 2.3.8, presented some variation in the RPA results. As Figure 9 shows, only Vegetation Cover presented small variation among the different stretches, suggesting the presence of small tree crowns in general because Tree Density varied more considerably. Furthermore, some variations in Tree Height, Tree Density and Grass Infestation reinforce the occurrence of different FR success that were indicated by photointerpretation.

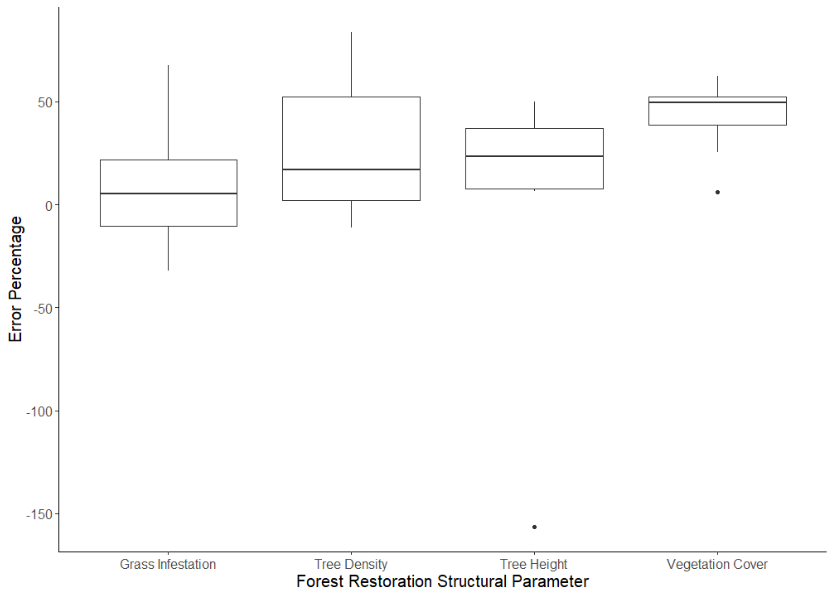

Figure 9. FR structural parameters of the stretches with different FR success varied from the fieldwork reference value, except Vegetation Cover. A variation in Tree Density and non-variation of Vegetation Cover suggest small tree crowns in general.

Figure 10 shows that the FR structural parameters presented some correlation between them. Such correlation suggests some ecological succession process: Grass Infestation has a high negative correlation with the development of trees; the taller the trees, the bigger the tree crowns (high correlation between Tree Height and Vegetation Cover); and many trees presented small tree crowns (medium correlation between Tree Density and Vegetation Cover).

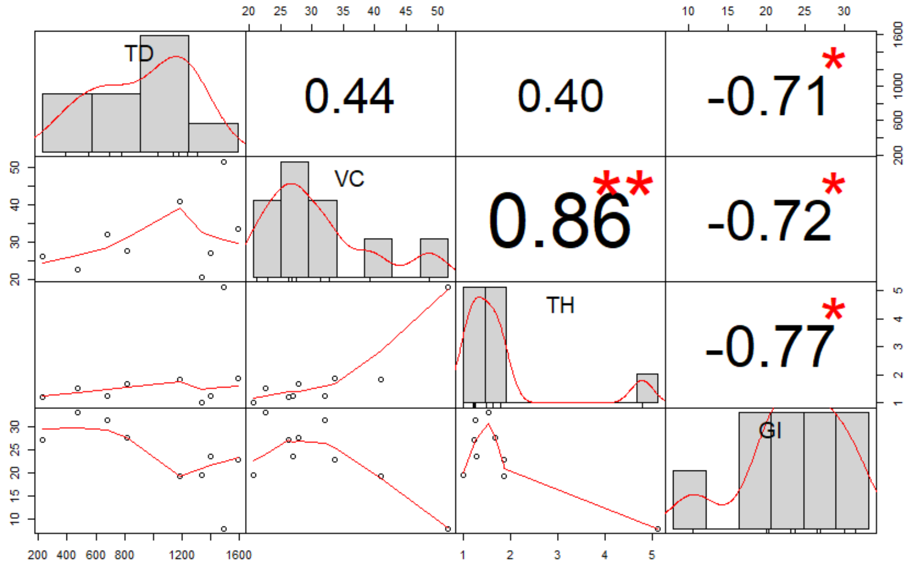

Figure 10. FR structural parameters Correlation Matrix between different FR stretches. In this symmetric matrix, the cells of the main diagonal shows a FR structural parameter (TD is Tree Density, VC is Vegetation Cover, TH is Tree Height, and GI is Grass Infestation) and its corresponding values in the different FR stretches. The other cells show the correlation value between different FR structural parameters, where the more asterisk ("*") symbol occurs, the more correlated two variables are.

4. Discussion: Lessons Learned

In this study, we present the Discussion section as lessons that were learned, and thus each lesson is presented as a subsection. The subsection title represents the lesson itself, while the corresponding text complements and discusses it. By highlighting each lesson as a subsection, we intend to make its discussion easier to be found in the manuscript.

4.1. Low-Cost RPA Is Capable of Accurately Mapping Forest Restoration (FR) Structural Parameters in Open Canopy Conditions

Although previous works accurately evaluated tree cover and tree height using low-cost RPA [44–46], this study evaluated four structural parameters (Vegetation Cover, Tree Height, Tree Density and Grass Infestation) in the context of FR and in a sloping area, which represents a common situation in the Brazilian Atlantic Forest Biome.

RPA works at the local scale only [47], but if a regional scale is desired, the Landsat satellite, although having a lower spatial resolution when compared to other remote sensing databases, showed potential for monitoring the vegetation expansion of FR projects throughout the years [48]. Still regarding FR monitoring at the regional scale, initiatives like the MapBiomas project (https://mapbiomas.org/, accessed on 15 June 2021) show the locations of secondary forests for free.

The Landsat free available satellite imagery may provide valuable information, but its spatial resolution generates inconsistencies when more refined data is needed to evaluate the FR [47]. Thus, each technology has advantages and disadvantages, and this work reinforces that low-cost RPA is a good alternative for collecting data to monitor the FR at the local level. Since low-cost RPA is capable of accurately mapping FR structural parameters in open canopy conditions, future studies shall evaluate FR areas with closed-canopy conditions.

4.2. To Improve the Accuracy of the Tree Height Measurement by Low-Cost RPA in All the FR Stages, a Possible but Expensive Solution would be Using Precise Global Navigation Satellite System (GNSS) Data

Although the Tree Height was accurate in this work, the CHM omitted trees that were slightly higher than grasses in the sloping area. To handle this situation, a flight prior to the tree growth using precise GNSS coordinates could obtain an accurate (or a literal) DTM. Then, after the FR process begins (after trees begin to grow), an accurate CHM would be possible due to a refined DTM availability for the future RPA data acquisition, which would also demand precise GNSS coordinates.

Besides checking if a precise DTM would include small trees in the CHM of sloping FR areas, the use of precise GNSS data would also confirm if the accuracy of the tree height measured using SfM-MVS increases even when the canopy closes. The use of traditional topography methods (when geodetic GNSS equipment and total station are required) generates a refined DTM in closed-canopy conditions, which allows accurate Tree Height measurements via SfM-MVS [49]. However, classic topography increases the costs of the projects due to the time spent in the field [50] and to the costs of the equipment [51], and thus the benefits of using ground control points for Tree Height measurement via RPA data collected before and after the tree growth must be carefully studied in the future.

To avoid collecting precise GNSS data on every RPA flight for the Tree Height measurement, survey markers can be installed on the FR surroundings, and thus the precise geographic coordinates can be collected only once. After collecting the precise GNSS coordinates, the survey markers can become ground control points (GCP) for the RPA data by putting visual targets above them before each RPA flight. The location of the survey markers has to be the FR surroundings because they must be visible on the RPA data after the canopy closes.

Alternatively, to avoid using survey markers or precise GNSS coordinates on every SfM-MVS cartographic data, collecting different RPA images of the same area along the FR evolution could enable an independent analysis of each orthomosaic until the canopy closes. Future studies may confirm if precise GNSS coordinates are necessary only for a precise DTM generation (when trees have not started to grow) and for the RPA images acquired after the canopy closes.

Tree Height is a relevant structural parameter because it is related to ecology [52], biomass [49,53], and biodiversity [53,54], and measuring it in closed-canopy conditions is not an issue in LiDAR systems [46,53,55]. However, LiDAR systems are considered more expensive, which is not ideal for the financial reality of developing countries [10]. Thus, more studies of Tree Height measurement by SfM-MVS in closed-canopy conditions must be conducted. Tree Height measured by RPA is a field of research that may benefit not only the FR and mature forests, but also different commercial plantations and crops [56].

4.3. Via Photointerpretation, RPA Can Identify Stretches with Different FR Success That Present Different Values of FR Structural Parameters

One of the advantages of RPA is that the entire FR area can be measured, and thus stretches with different degrees of FR success were visually identified. The values of the FR structural parameters in these stretches presented some variation from the fieldwork reference value, as indicated by the standard deviation of the boxplots shown in Figure 9.

Although the RPA has the advantage of identifying stretches with different FR success, such benefit occurs at the local scale only. If a regional FR monitoring scale is required, Landsat images, due to its spatial resolution, have the potential to identify only considerable increases in vegetation cover [48].

The possibility of identifying stretches with different FR success via photointerpretation of the low-cost RPA orthomosaic reinforces another advantage of monitoring FR using high spatial resolution images: it provides valuable information in open-canopy conditions even if no more data of the FR site, like field plots, is available. Since photointerpretation of low-cost RPA orthomosaic generates reference data for Tree Cover, Tree Density and Grass Infestation, which are relevant structural parameters, managers can check stretches with less FR success that may need some intervention using RPA data only.

Besides being capable of identifying stretches with different FR success, the FR structural parameters evaluated in this study were based on the Rio de Janeiro local environmental agency [11], and Tree Height was the only FR structural parameter that demanded a traditional fieldwork for reference data acquisition in open canopy conditions. Traditional fieldworks are necessary to evaluate the computational 3D modeling because it is not possible to check tree heights using a photointerpretation of the CHM. Even LiDAR systems that accurately measured Tree Height demanded traditional fieldwork for acquiring reference data [46,53,55]. Thus, Tree Height is the only FR structural parameter evaluated in this study that demands fieldwork to assess its remote sensing accuracy, which reinforces that low-cost RPA data register valuable information for FR projects even if no field plot data is available.

4.4. RGB Limitations for Identifying Different Tree Species Reinforced That Biodiversity and Remote Sensing Constitute a Specific Field of Research and That Traditional Fieldwork Will Continue Being Necessary in the Future

Although modern Computer Vision techniques, such as Deep Learning, have demonstrated that low-cost RPA can be used to identify palm species in the Amazon [32] or tree species in a German forest [33], it is still not possible to handle the biodiversity of Brazilian FR projects solely via high-resolution RGB imagery. The tree species of the Atlantic Forest Biome in this study looked very similar in the RPA imagery, but since the Biodiversity parameter is relevant for FR projects, future works must check if other species, which were not present in the study area, are distinguishable in high-resolution RGB images. These future studies must generate two databases with precise Global Navigation Satellite Systems (GNSS) geographic coordinates: the low-cost RPA data, which must present ground control points to improve its cartographic precision (1); and the tree species location, which must be a layer where each tree has a precise geographic coordinate associated with its corresponding species. These two databases will make it possible to verify which tree species are distinguishable via photointerpretation.

In this work, even if the two databases mentioned in the previous paragraph (RPA data and tree species location with precise GNSS coordinates) were available, the Biodiversity parameter would still not be possible to be measured via low-cost RPA because photointerpretation could not distinguish different tree species. After all, the targets in the images must be visually distinguishable for a proper reference data [35,39]. A possible solution for this low-cost RPA limitation for recognizing different species may be the flowers of the trees. The flowers can make some tree species distinguishable via photointerpretation, but the remote sensing data must be collected in the flowering period [42], which reinforces the challenge involving Biodiversity and remote sensing.

Another alternative for measuring the Biodiversity parameter via remote sensing would be an estimation of the number of species in a FR site instead of the identification of the species of each tree. When dealing with the number of species, an unsupervised classification could be applied, but reference data would still be necessary [35,57]. In this study, as previously mentioned, there was no reliable Biodiversity reference data for remote sensing estimations due to a significant similarity between the different tree species in the RPA imagery.

Almeida et al. [53] used a refined remote sensing dataset provided by a LiDAR system and also mentioned a biodiversity challenge in the Atlantic Forest Biome because the authors accurately measured canopy structure and above-ground biomass of FR areas, but not species richness. Alonzo et al. [58] used LiDAR and hyperspectral sensors to map 29 tree species considering 30 different remote sensing classes: 29 classes corresponded to 29 different tree species, while 1 class involved different and non-frequent tree species. Thus, regarding the biodiversity challenge, even if multispectral, hyperspectral, or LiDAR sensors prove to be capable of automatically identifying tropical rainforest species in the near future, the costs of such sensors must decrease considerably if a practical FR monitoring protocol is desired. Traditional fieldwork will therefore continue being necessary and remote sensing may be applied using applications onboard smartphones and tablets, like Agrotag [59], for monitoring the FR biodiversity.

Applications onboard smartphones and tablets like Agrotag can take pictures at the ground level of the tree species and can also share the FR monitoring data collected by field plots on an online Geographic Information System (GIS) platform. Future studies may evaluate if using a low-cost RPA for measuring the structural parameters and an application onboard smartphones and tablets for measuring the Biodiversity parameters are capable of accurately providing a full FR monitoring report.

5. Conclusions

For the development of a practical FR monitoring protocol, low-cost RPA was found to be accurate for the measurement of the FR structural parameters. Only Grass Infestation, which is the least important indicator, presented medium accuracy. In addition to improving the accuracy of the Grass Infestation parameter, future studies must evaluate the optimal remote sensing techniques for FR projects of different ages, with a particular focus on how low-cost RPA can accurately measure the FR structural parameters when the canopy is closed. After all, each FR stage will require different remote sensing techniques.

Although low-cost RPA can accurately measure the structural parameters, it cannot accurately measure the FR biodiversity parameter in the Brazilian Atlantic Forest, and thus traditional fieldwork will continue being necessary. It may be possible to utilize an RPA and then use field plots for biodiversity monitoring only, but this would require FR consultants and environmental agencies to evaluate the costs of adding a remote sensing professional to their teams.

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Appendix A. Field Plot Replication in RPA Imagery

Appendix A.1. Methods: Field Plot Replication in RPA Imagery

As mentioned in Section 2.3.2, a field plot replication in the RPA image was initially motivated to study the Biodiversity parameter, but since all trees were very similar in the RPA image, an evaluation of the FR structural parameters inside the polygons that represent the field plots was conducted.

The rectangle shapefiles that represented the 25 × 4 m field plots were generated like the fieldwork procedures, where the field plots coordinates correspond to the southernmost latitude and middle longitude of the field plot rectangles. From these coordinates, 25 m lines were generated with 0° Azimuth. The field plot rectangle is then completed by considering 2 m from each perpendicular direction of the 25 m line, forming a 25 × 4 m plot rectangle [11]. Figures A1 and A2 illustrates examples of this field plot rectangle procedure.

When analyzing the RPA results inside the field plot rectangles, two different reference data were considered due to the cartographic uncertainty of the orthomosaic and of the field plot location. These two reference data were the photointerpretation of the field plot rectangles (photointerpretation has no cartographic uncertainty with the RPA results because both came from the same database) and the fieldwork data of each field plot. The differences between the RPA accuracy results considering these two reference data were then recorded and analyzed. The accuracy measurement unit is described in Appendix A.2.

When generating the photointerpretation of the field plots rectangles as Figure A2 shows, the authors stated that the position of the 25-m line considerably influences Vegetation Cover and Grass Infestation parameters. To quantitatively measure such an influence, an experiment was conducted where Vegetation Cover and Grass Infestation were measured in different positions over the RPA image, as explained in the next paragraphs.

In traditional fieldwork, Vegetation Cover is obtained by stretching a 25 m measuring tape on the floor. The length of the measuring tape covered by trees is noted and then divided by 25 m. If, for example, the number of meters covered by trees is 25 or 12.5, you get 100% and 50% of Vegetation Cover, respectively. Figure A1 illustrates the fieldwork procedures for the Vegetation Cover measuring procedure.

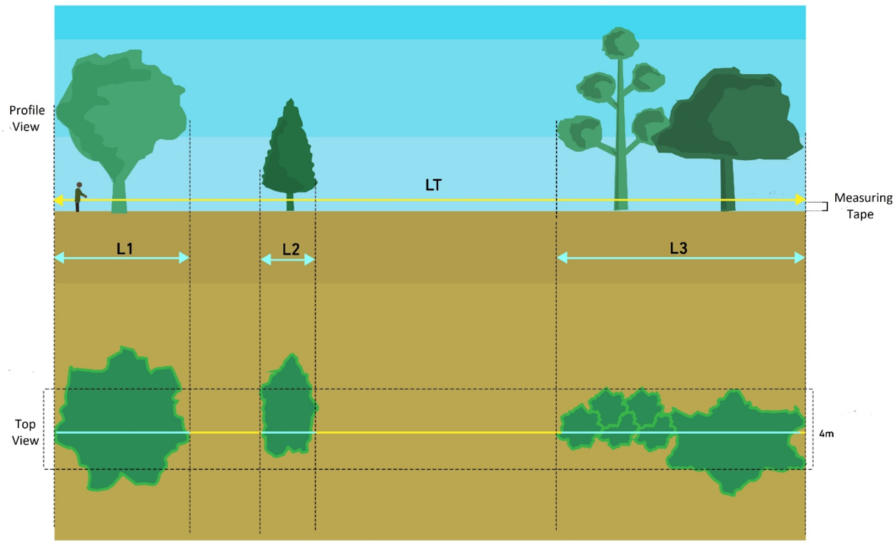

Figure A1. Vegetation Cover measuring procedure on a 25 × 4 m plot, where LT is Linear Totality. In the fieldwork procedures, LT is equal to 25 m, and the field plot is defined by considering 2 m from each LT perpendicular direction, forming then a 25 × 4 m plot. L1, L2, and L3 are examples of linear measurements in LT that are covered by trees. Thus, Vegetation Cover is the sum of L1, L2, and L3 divided by LT. Source: adapted from INEA [11].

When applied to RPA imagery, this method can be subject to some issues because Vegetation Cover is an area measurement (two dimensions), and the measuring tape measures lengths (one dimension). As can be seen by Figure A1, if the measuring tape moves 2 m to the left or the right in an RPA image, the Vegetation Cover parameter may considerably vary.

To verify if moving the measuring tape 2 m to the left or the right considerably affects Vegetation Cover on RPA imagery, an experiment was conducted. In such an experiment, the amount of line that covered trees was verified by photointerpretation in three different positions for each field plot. In the first position, the 25-m line is in the field plot coordinate (which is the position for measuring Vegetation Cover according to the fieldwork procedures). In the second and third positions, the line shifted 2 m to the left (west direction) and 2 m to the right (east direction). After verifying the amount of tree cover on these positions, the variation (between the first position and the other two positions) was noted in percentage. Regarding the 2 m value, it represents an usual imprecision value of a common GNSS equipment [60], and it is also the value that the fieldwork procedures move (to the left and the right) to generate a 25 × 4 m plot. Figure A2 illustrates this 2-m shifting process evaluation.

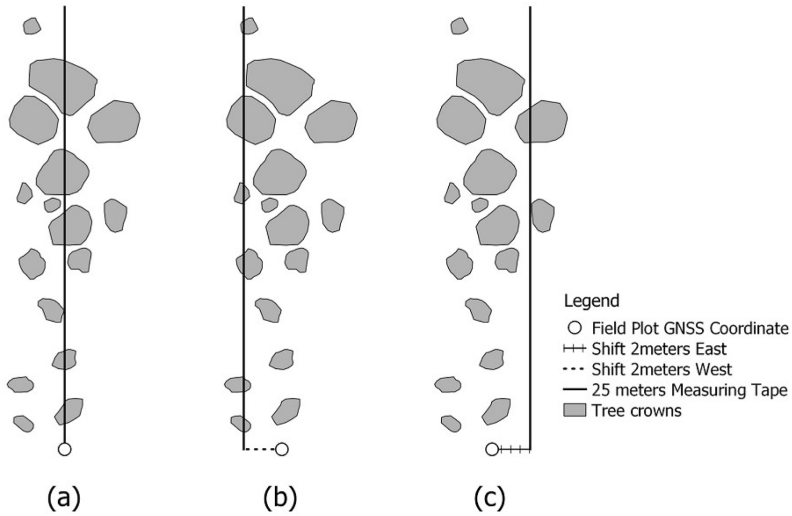

Figure A2. An experiment to quantitatively measure the influence of the measuring tape position in Vegetation Cover acquisition if trying to replicate the fieldwork procedures on RPA imagery. Vegetation Cover value from the middle longitude of the field plot, which is where the measuring tape is positioned in the fieldwork procedures, (**a**) was compared to the Vegetation Cover value when moving the measuring tape 2 m in the west direction (**b**) and the east direction (**c**).

If this experiment, illustrated in Figure A2, confirms that Vegetation Cover considerably varies when moving the line shapefile, remote sensing may be reinforced as an alternative to improve this variable measurement. It would also verify that replicating traditional fieldwork procedures over RPA images is not a good idea.

Such an experiment of moving the measuring tape 2 m to the right and the left was also made for Grass Infestation because it has the same Vegetation Cover fieldwork procedures that are illustrated in Figure A1.

It must be mentioned that when comparing RPA and fieldwork results, some issues found that the overflown study area did not involve the whole area monitored by fieldwork results. Overall, 19 out of 28 field plots, which corresponds to 23.45 out of 28.55 hectares of the FR area, were covered by the RPA imagery, while Vegetation Cover and Grass Infestation fieldwork values were not recorded for each field plot (only the final value was recorded). This means that 17.8%$((28.55-23.45)/28.55=0.178)$ of the area monitored by fieldwork procedures, and not by RPA imagery, contained 32% of the field plots. Regarding those not overflown field plots, Google Earth's free available imagery showed by photointerpretation that these were the FR areas with the highest tree cover (canopy was almost closed), which could also suggest the highest values of other FR structural parameters.

Appendix A.2. FR Structural Parameters Accuracy Evaluation Inside Field Plots

When replicating the FR structural parameters inside the field plots, it is expected for RPA results to present values closer to the photointerpretation reference data than to the fieldwork reference data because there is no cartographic uncertainty.

RPA classification results inside the field plot rectangles had their accuracy evaluated via Error Percentage [37], where zero Error Percentage means 100% accuracy, positive percentage values are omission errors, and negative percentage values are commission errors. For example, an Error Percentage of 5% means FR structural parameters lacked 5% of the reference data value (omission error), and an Error Percentage of −4% means FR structural parameters exceeded 4% of the reference data value (commission error). Equation (8) shows the calculation of Error Percentage, where "Reference" can be photointerpretation or fieldwork and "Results" are the RPA results automatically obtained.

The variation in Vegetation Cover and Grass Infestation in the experiment illustrated in Figure A2 was also calculated like Equation (8), but considering that "Reference" in Equation (8) is the "25 meters Measuring Tape" in Figure A2, and "Results" in Equation (8) is "Shift 2 meters East" or "Shift 2 meters West" in Figure A2. These variations in Vegetation Cover and Grass Infestation were measured for each field plot.

Appendix A.3. Results: RPA and Fieldwork Data Comparison Inside Field Plot Rectangles

Although Grass Infestation was the only FR structural parameter with medium accuracy as Section 3.1 shows, Table A1 shows some differences between RPA and fieldwork results. Such differences occurred because the RPA orthomosaic did not cover 33% of the whole field plots, as mentioned in Appendix A.1. Furthermore, stretches with non-vegetated and seedlings predominance (Nv and NvS in Figure 3) occupied 52.3% of the RPA study area, and these areas presented 21.4% of the field plots.

Table A1. RPA and fieldwork data comparison.

FR Structural Parameter	RPA	Fieldwork
Vegetation Cover (%)	27.80	55
Tree Density (trees/hectare)	814	1428
Tree Height (meters)	1.68	2
Grass Infestation (%)	27.57	25

When analyzing RPA results inside field plot rectangles, the Error Percentage was generally smaller with photointerpretation reference data than with fieldwork reference data, as Figure A3 shows.

Regarding Grass Infestation, a significant variation of its Error Percentage is presented in Figure A3. As Figure A4 shows, Grass Infestation may considerably vary if moving the measuring tape (or the 25-m line shapefile) two meters to the left or right, as described in Appendix A.1. Such variation reinforces remote sensing as a proper way for measuring Vegetation Cover and Grass Infestation.

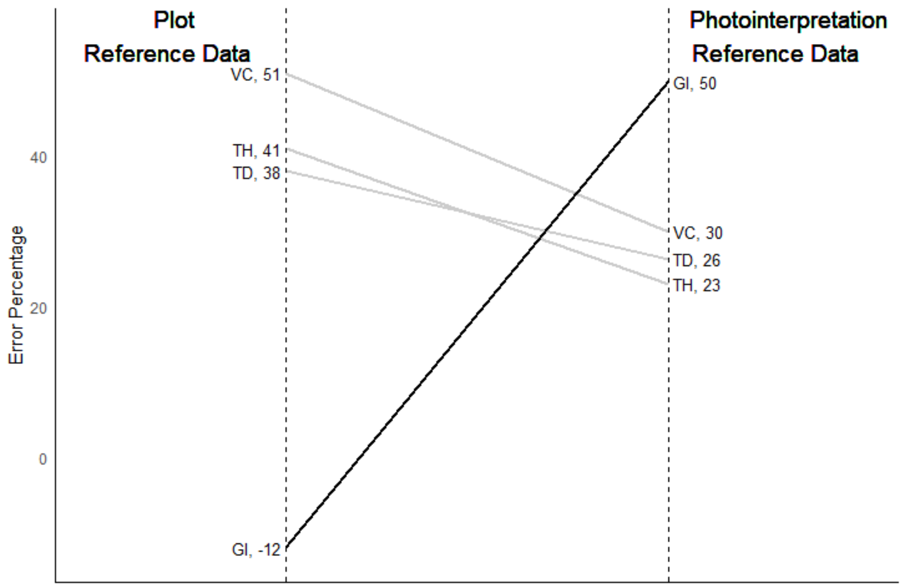

Figure A3. RPA results' Error Percentage inside field plots when considering two reference data: photointerpretation and fieldwork.

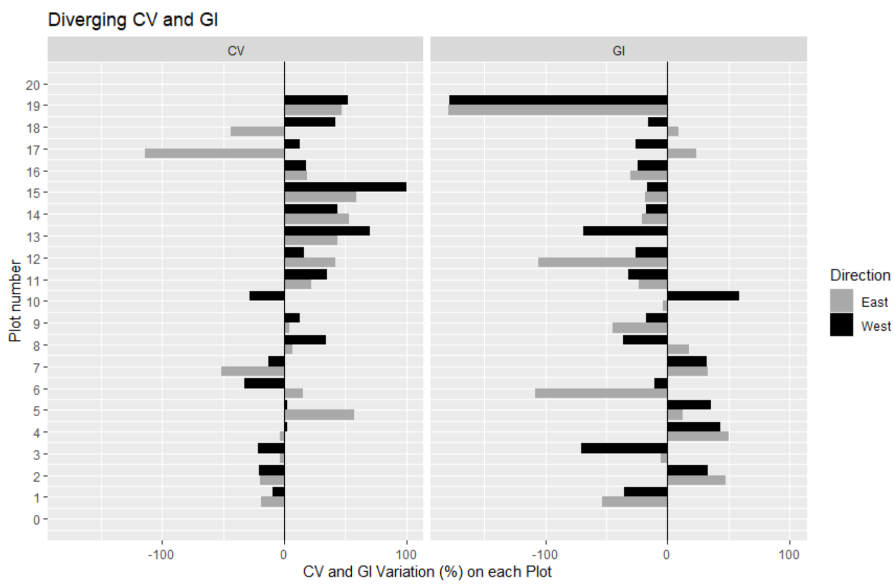

Figure A4. When measuring Vegetation Cover and Grass Infestation by a 25-m line shapefile, which is a simulation of the traditional fieldwork procedure, these FR structural parameters significantly varied when moving the measuring line 2 m in east and west directions. The registered Error Percentage presented mean and standard deviation equal to 11.48 ± 39.45 for Vegetation Cover and −20.3 ± 54.61 for Grass Infestation.

Appendix A.4. Discussion: Lessons Learned when Replicating Field Plots in RPA Imagery

RPA and fieldwork results differ when whole field plots are not overflown. RPA and fieldwork results presented quite some differences between them because 17.9% of the area analyzed by fieldwork was not included in the RPA study area. Despite such differences, RPA can contribute to the traditional fieldwork sampling process because it registers whole project areas, so it is possible to identify stretches with different FR success that lack or exceed field plot samples. For instance, stretches with grass predominance occupied 52.3% of the RPA study area, but presented 21.4% of the field plots.

Due to the cartographic uncertainty between fieldwork data and RPA imagery, the RPA results get closer to the photointerpretation than to the fieldwork data of each field plot. Error Percentage inside field plots was smaller with photointerpretation reference data than with fieldwork reference data, as Figure A3 shows. If both the RPA orthomosaic and the fieldwork data presented precise GNSS coordinates, the Error Percentage variation shown in Figure A3 would probably be smaller. However, one must consider that precise GNSS coordinates increase the fieldwork costs [50].

Measuring Vegetation Cover and Grass Infestation over RPA image by field plots procedure (25-m line) generates inconsistencies, reinforcing the RPA potential in measuring these variables by remote sensing techniques. Since Vegetation Cover and Grass Infestation are a two-dimension variable, measuring them by a line (one dimension) using RPA imagery is a source of many errors. The experiment of moving the line shapefile 2 m to the left and right showed significant variation in Vegetation Cover and Grass Infestation results, as illustrated in Figure A4. This fact confirmed that linear field measurements based on measuring tape should not be used in RPA images.

If the FR professionals wish to use precise GNSS coordinates to record the field plots location, they may consider turning the fieldwork rectangular plots into the Quadrat Method [61], which uses points. The Rio de Janeiro State official FR monitoring methodology has the option of using points instead of lines for field plots design. In these situations, each sampling point would be a precise GNSS coordinate (or also a ground control point of the RPA image), and the fieldwork analysts could collect the phytosociological data while the geodetic GNSS tracks its location. However, precise GNSS data usage increases the fieldwork costs [50].

Remote sensing and forest inventory are different sciences, but their final overall results must be similar. Although an obvious lesson, photointerpretation and traditional fieldwork presented some differences in this work because the whole FR area was not overflown. Furthermore, when trying to replicate field plots in the RPA image, the lack of precise GNSS coordinates also generated some differences between photointerpretation and fieldwork results. However, the two methodologies were able to state an ecological succession process in the study area.

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