UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE BIOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

Tese de Doutorado

Processos ecossistêmicos e funcionalidade de florestas em restauração

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Orientadora: Dra. Sandra Cristina Müller

Porto Alegre, 13 de junho de 2017

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Milena Fermina Rosenfield

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À minha vó Lídia,
pelo carinho, atenção e incentivo
à formação acadêmica dos filhos e netos.

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RESUMO

A restauração florestal é mais do que somente plantar árvores. É necessário que haja o monitoramento do desenvolvimento da floresta no que diz respeito tanto a parâmetros estruturais e florísticos, mas também aos processos ecológicos. Esses processos propiciam as interações entre as espécies e promovem a funcionalidade do sistema, provendo serviços ecossistêmicos. Por isso, é necessário, além de monitorar o crescimento da vegetação, avaliar se o ecossistema está operando da forma como seria esperado. O objetivo desta tese é abordar questões referentes aos processos ecológicos e atributos funcionais em áreas florestais em processo de restauração. No primeiro capítulo, foi realizada uma revisão sistemática com o intuito de identificar os processos ecológicos e as variáveis que são medidas em estudos de restauração florestal. Os três capítulos seguintes foram baseados na coleta de dados em três sítios de estudo, situados no Estado do Rio Grande do Sul, Brasil. Foram coletados dados em florestas que tiveram intervenções de restauração (com aproximadamente 10 anos de desenvolvimento), bem como em florestas de remanescentes (utilizadas como sistema de referência). Além da amostragem da vegetação arbórea, foram coletados dados de diversos processos ecológicos, relacionados à ciclagem de nutrientes (decomposição, detritivoria e qualidade da serapilheira e do solo), produtividade (biomassa arbórea acima do solo e biomassa de folhas) e recrutamento (regeneração natural), bem como informações sobre atributos foliares, reprodutivos e de crescimento das espécies. Os resultados obtidos para cada um dos capítulos indicaram que: (1) os processos mais comumente avaliados foram aqueles relacionados à ciclagem de nutrientes, seguido por resiliência do ecossistema, produtividade, relações hídricas e interações bióticas; além disso foi identificado que os resultados positivos das ações de restauração nos processos ecológicos aumentam a medida que os sítios se tornam mais antigos; (2) áreas em restauração ainda diferem de suas respectivas florestas de referência para quase todas as variáveis analisadas, mas, ao contrário da nossa expectativa inicial, as diferenças foram maiores quando considerados os parâmetros estruturais da vegetação, indicando que os processos ecológicos podem se restabelecer antes mesmo da floresta atingir sua completa complexidade estrutural; (3) as variáveis que mais afetaram os processos ecológicos foram aquelas relacionadas aos atributos funcionais, tendo a riqueza de espécies na comunidade apenas um papel secundário na variação dos processos ecológicos estudados; além disso, tanto variáveis de composição funcional, quanto de diversidade funcional tiveram influência nos processos; e (4) modelos utilizados para avaliar a semelhança funcional entre restauração e referência indicaram que a comunidade presente no sub-bosque da restauração apresenta uma maior semelhança funcional com o sistema de referência do que a comunidade do dossel, indicando que as espécies utilizadas nos plantios diferem consideravelmente em sua composição funcional das áreas de referência. Esse estudo ressalta a importância de se compreender melhor os processos ecológicos em ecossistemas florestais e sua aplicação na avaliação do funcionamento de áreas em processo de restauração. O monitoramento desses sítios deve ser realizado a longo prazo de forma a verificar as variações ao longo do desenvolvimento florestal e avaliar as trajetórias sucessionais, sugerindo ações de manejo se necessário.

Palavras-chave: atributos funcionais; ecologia funcional; floresta subtropical; funções ecossistêmicas; multifuncionalidade.

ABSTRACT

Forest restoration is more than just planting trees. It is required that forest growth is monitored both by measuring structural and floristic parameters, but also ecological processes. These processes provide interactions among species and promote ecosystem functionality, also offering important ecosystem services. Thus, it is necessary that besides monitoring vegetation growth, it should be evaluated if the ecosystem is operating as would be expected. The objective of this thesis it to address questions related to the ecological processes and functional traits in forests sites undergoing restoration. In the first chapter, we performed a systematic review in order to identify the ecological processes and the variables measured in forest restoration studies. The following three chapters were based on data collected in three study sites, located in the State of Rio Grande do Sul, Brazil. We collected data in forests subjected to restoration (approximately 10 years-old) and more conserved forests not subjected to restoration (used as reference ecosystem). Besides sampling tree components, we collected data on several ecological processes, related to nutrient cycling (decomposition, detritivory and litter and soil quality), productivity (aboveground tree biomass and litter biomass) and recruitment (natural regeneration), as well as information on leaf, reproductive and growth traits of species. The results obtained for each chapter indicated that: (1) the processes that were more frequently measured were the ones related to nutrient cycling, followed by ecosystem resilience, productivity, water relations and biotic interactions; additionally, we identified that positive results of restoration interventions on the ecological processes increased as sites became older; (2) restoration sites still differed from their reference ecosystems for all variables evaluated, but opposed to what we initially expected, these differences were even greater when we considered the structural parameters from the vegetation, suggesting that ecological processes may recover even before the full reestablishment of forest complexity; (3) the variables that most affected ecological processes were the ones related to functional traits, and community species richness had only a secondary role in the variation of ecological processes; in addition, both variables related to functional composition and functional diversity affected the ecological processes evaluated; and (4) the models used to evaluate functional similarity between restoration and reference indicated that the community growing in the understory of the restoration site is functionally more similar to the reference than the canopy community, suggesting that the species used in restoration plantings differ considerably in functional composition from reference sites. This study highlights the importance of ecological processes in forest ecosystems and its application in the evaluation of the functioning of sites undergoing restoration. Monitoring of these sites should be performed for a long period, in order to verify changes during forest growth and to evaluate sucessional trajectories, suggesting management actions if necessary.

Keywords: ecosystem function; functional ecology; functional traits; multifunctionality; subtropical forest.

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INTRODUÇÃO GERAL

1. Restauração ecológica

A ecologia da restauração é definida pela *Society for Ecological Restoration International* (SER 2004) como o processo que consiste em auxiliar a recuperação de um ecossistema que foi degradado, impactado ou destruído. Trata-se de uma atividade intencional que inicia ou acelera a recuperação do ecossistema no que diz respeito aos processos funcionais, composição de espécies, estrutura da comunidade e resistência/resiliência a distúrbios (SER 2004), aumentando sua complexidade estrutural e funcional (Aronson *et al.* 2006). A restauração ecológica tem como meta restaurar condições e estrutura da vegetação, semelhante ao que ocorria antes do evento de degradação (SER 2004). Por isso, ela leva em consideração o ecossistema de referência (Higgs *et al.* 2014), sendo comumente utilizados fragmentos conservados existentes na região (semelhantes ao que ocorria antes do fator de degradação). Por mais que o ecossistema de referência represente uma base de comparação, um guia para a avaliação do projeto de restauração, deve-se levar em conta a possibilidade de múltiplas trajetórias (Higgs *et al.* 2014), uma vez que a trajetória da restauração é indefinida.

De forma geral a restauração ecológica é embasada nos conceitos gerais estudados em ecologia, como sucessão ecológica, fragmentação, dinâmica das comunidades. A partir disso são definidos os objetivos e estratégias do projeto de restauração, com base no sistema de referência e considerando os recursos disponíveis para sua execução. Considerando o estado de degradação local, são definidas as técnicas que serão empregadas, bem como a necessidade ou não de manejo ao longo do tempo. Por fim, o projeto deve ser monitorado de forma a avaliar o sucesso da restauração, através de métricas de estrutura da vegetação e diversidade de espécies, processos ecológicos e questões socioeconômicas (Overbeck *et al.*

2016). Segundo a SER (2004), o ambiente restaurado deve apresentar espécies nativas características do local, diversidade de grupos funcionais, ambiente físico adequado e funções ecossistêmicas estabelecidas; deve ainda ser integrado com a matriz ecológica, com redução de ameaças potenciais e ser um ecossistema resiliente e autossustentável.

As técnicas geralmente utilizadas em restauração buscam estimular a regeneração natural e o processo de sucessão ecológica (Aerts & Honnay 2011), propiciando o estabelecimento de novas espécies. De maneira geral, a restauração de florestas é realizada através de plantio de mudas (Ruiz-Jaen & Aide 2005), buscando uma alta diversificação no número de espécies nativas plantadas, de preferência com aquelas que ocorrem na floresta de referência (Lamb 2005; Rodrigues *et al.* 2009). Há ainda técnicas de semeadura direta, transposição de solo, transposição de galharia e construção de poleiros artificiais, entre outras (Reis *et al.* 2003; Bechara *et al.* 2007). Essas técnicas visam criar núcleos de diversidade ou atrair dispersores para a área degradada. Entretanto, em vastas áreas degradadas e com o objetivo de acelerar a recuperação florestal, a principal opção ainda é o plantio de mudas, em forma de plantio em linhas ou em ilhas de diversidade (nucleação) (Corbin & Holl 2012).

A matriz da paisagem, que circunda a área degradada, é especialmente importante, pois a presença de fragmentos florestais no entorno propicia fonte de propágulos para a área em processo de restauração (Martínez-Ramos *et al.* 2016), aumentando da riqueza de espécies (Melo & Durigan 2007). A dispersão de sementes é um dos principais limitantes para a recuperação de ecossistemas florestais (Holl 1999). Por meio de dispersores, que trazem sementes e frutos oriundos da floresta preservada, é possível ter a colonização de novas espécies, levando ao aumento da riqueza de espécies e, potencialmente, maior resiliência do sistema.

A recuperação da vegetação em áreas em processo de restauração não segue uma trajetória definida (Norden *et al.* 2015) e muitos são os estados possíveis para o desenvolvimento do sistema (Bullock *et al.* 2011), por vezes distintos da meta estabelecida com base na referência (ecossistema preservado). Muitos estudos mostram uma recuperação lenta dos parâmetros florísticos e estruturais da vegetação (Liebsch, Marques & Goldenberg 2008; Dent, Dewalt & Denslow 2013). Por isso, o monitoramento ao longo do tempo é necessário para avaliar como os parâmetros avaliados mudam após as intervenções de restauração e ao longo da sucessão (Suganuma & Durigan 2015). O monitoramento permite avaliar a necessidade de atividades de manejo, de forma a transpor barreiras encontradas, como por exemplo colonização de espécies invasoras ou estagnação do processo. No caso de limitação de dispersão, uma das técnicas de manejo utilizadas é o plantio de enriquecimento ou a condução da regeneração natural (Sampaio, Holl & Scariot 2007).

A avaliação desses projetos é feita pelo acompanhamento dos plantios, analisando-se a estrutura da vegetação, riqueza/diversidade de espécies e, menos frequentemente, o desenvolvimento dos processos ecossistêmicos (Ruiz-Jaen & Aide 2005; Rodrigues *et al.* 2009). As avaliações que não consideram explicitamente os processos ecossistêmicos assumem que o restabelecimento da riqueza de espécies e da estrutura da vegetação proporciona a recuperação dos processos ecossistêmicos (Ruiz-Jaen & Aide 2005). Essa premissa, entretanto, não considera que as funções e processos ecossistêmicos, tais como decomposição foliar, produtividade primária, regeneração natural e dispersão de sementes, entre outros, podem não se restabelecer na mesma velocidade que o crescimento da vegetação acima do solo (Palmer, Ambrose & Poff 1997; Cortina *et al.* 2006; Matzek, Warren & Fisher 2016). A busca por indicadores que melhor indicam o sucesso do projeto de restauração é uma atividade contínua, sujeita a intensas discussões (ver debate envolvendo Reid 2015; Suganuma & Durigan 2015; Brancalion & Holl 2016). É difícil atingir um consenso do que deve ou não ser medido, entretanto é indicada uma avaliação que considere informações referentes à estrutura da vegetação, diversidade de espécies e processos ecossistêmicos de forma conjunta (Ruiz-Jaén & Aide 2005; Suding *et al.* 2015).

Aparte dos aspectos teóricos e técnicos associados à restauração ecológica, esta é uma atividade que visa reduzir danos ambientais decorrentes de diversos usos antrópicos. Portanto, é importante conhecer a legislação local/estadual e nacional para potencializar as oportunidades de recuperação de ambientes degradados. A lei mais recente que versa sobre a proteção da vegetação nativa é a Lei nº 12.651/2012 – Lei de Proteção da Vegetação Nativa (também conhecida – erroneamente – como Novo Código Florestal). Ela estabelece os limites das Áreas de Preservação Permanente (APPs), por exemplo nas margens de recursos hídricos, e da Reserva Legal (RL) de modo a preservar ou recuperar, nos casos de degradação, fragmentos e corredores de vegetação nativa. Ela também determina que áreas degradadas devem ser recuperadas de forma a mitigar os danos ambientais causados. Nesse sentido, foi criada a Política Nacional de Recuperação da Vegetação Nativa, em vigor através do Decreto nº 8.972/2017, cujo objetivo é viabilizar as ações de recuperação indicadas na Lei 12.651/2012. Ela prevê a criação do Plano Nacional de Recuperação da Vegetação Nativa (PLANAVEG), que objetiva estabelecer estratégias a longo prazo para potencializar as atividades de restauração, orientando desde a sensibilização dos envolvidos na restauração até o estímulo à cadeira produtiva, através de mecanismos financeiros e ações de pesquisa e desenvolvimento, de forma a viabilizar a execução dos projetos de restauração e a recuperação da biodiversidade. Entretanto, o monitoramento das ações de restauração, em geral, é realizado por um curto e insuficiente período, cerca de 3-4 anos, durante o qual não há indicação clara das métricas e parâmetros que devem ser monitorados para avaliação do sucesso da restauração. Nesse contexto, a lei mais avançada para monitoramento das áreas de restauração é a Resolução SMA nº 32/2014, em vigor no Estado de São Paulo – SP (Chaves *et al.* 2015). Ela estabelece orientações, diretrizes e critérios sobre a restauração ecológica em

SP. Através de valores de referência que devem ser atingidos ao longo da recuperação do ecossistema, o monitoramento deve considerar a cobertura do solo com vegetação nativa, bem como a densidade e riqueza de indivíduos regenerantes ao longo de cerca de 15 anos da implantação do projeto. Não há no Estado do Rio Grande do Sul lei específica sobre o monitoramento dos projetos de restauração, sendo utilizada como modelo a Instrução Normativa nº 04/2011, que trata sobre a elaboração de Projetos de Recuperação de Áreas Degradadas (PRADs).

2. Processos ecológicos e serviços ecossistêmicos

2.1 Processos ecológicos

Processos ecológicos envolvem interações entre componentes bióticos e abióticos dos ecossistemas, bem como relações no nível da comunidade. Esses processos envolvem transferência de energia ou matéria e são normalmente estimados em termos de taxas, por exemplo, produção ou decomposição, mas também podem ser caracterizados pela regeneração natural e dispersão de sementes. Eles são indispensáveis para a manutenção do ecossistema uma vez que estão associados a interações entre os organismos. Nesse sentido, podemos citar estoque de biomassa, disponibilidade de nutrientes no solo, regeneração natural, dispersão de sementes, polinização, entre outros, sendo muito importantes no contexto da restauração de ambientes degradados. No que diz respeito aos processos ecológicos, uma vez que existe grande número de processos que ocorrem nos diversos ambientes naturais, aqui serão abordados processos importantes na restauração florestal e que foram estudados no contexto da presente tese, processos esses relacionados à ciclagem de nutrientes, produtividade e regeneração natural.

A ciclagem de nutrientes consiste da ciclagem de componentes orgânicos e inorgânicos que promovem a disponibilidade de nutrientes para o crescimento das plantas

(Van Der Heijden, Bardgett & Van Straalen 2008). Bactérias, fungos e invertebrados são responsáveis pela ciclagem de nutrientes e geram efeitos tanto positivos, quanto negativos no crescimento das plantas através de decomposição da serapilheira, mineralização de nitrogênio, imobilização de nutrientes e atuando como patógenos (Wardle *et al.* 2004; Van Der Heijden *et al.* 2008). A decomposição da serapilheira envolve fatores abióticos, dependentes do clima, e fatores bióticos, tais como qualidade do material vegetal e presença ou composição dos organismos de solo (Couteaux, Bottner & Berg 1995; Zhang *et al.* 2008). Modificações na estrutura (e.g. abundância, diversidade e caracterização funcional) e composição de espécies vegetais em um ambiente influenciam a decomposição do material (Podgaiski & Rodrigues 2010), uma vez que proporcionam novas condições, habitat e recursos diferentes para a fauna do solo.

A produtividade primária e a ciclagem de nutrientes estão fortemente relacionados (Guariguata & Ostertag 2001). As plantas são fontes de carbono para os decompositores do solo e estes promovem a quebra do material morto e a disponibilização de nutrientes no solo, tornando os elementos novamente disponíveis às plantas (Wardle 1999). A produtividade primária líquida consiste na diferença entre o que é produzido através da fotossíntese e perdido através da respiração das plantas (Clark *et al.* 2001). De forma prática, ela pode ser definida pelo total de matéria orgânica nova produzida em um intervalo de tempo, podendo ser avaliada de duas formas distintas: através da biomassa viva acumulada nas plantas ou pela produção de serapilheira, que representa o que volta ao solo em forma de matéria orgânica morta (Clark *et al.* 2001). A dinâmica da produtividade e do estoque de biomassa se modifica durante ao longo sucessão, bem como durante no processo de restauração. Em estágios iniciais, a produtividade é alta, com grande produção de biomassa (Marin-Spiotta, Ostertag & Silver 2007), geralmente alocada em tecidos de aquisição de recursos (folhas e raízes finas), o que resulta em alta produção de serapilheira e baixa produção de madeira (Guariguata &

Ostertag 2001). Em florestas avançadas, o estoque de biomassa é alto (alocado nos tecidos de sustentação), mas a taxa de acúmulo de biomassa é mais baixa (Guariguata & Ostertag 2001; Gehring, Denich & Vlek 2005; Marin-Spiotta *et al.* 2007).

A regeneração natural ou o recrutamento de novos indivíduos na comunidade depende da chegada de propágulos, resistência à predação, germinação e sobrevivência e crescimento das plântulas (Holl *et al.* 2000). A distância de fontes de propágulos, limitação de nutrientes e competição com espécies herbáceas em áreas degradadas influenciam negativamente a regeneração natural. Nesse sentido, as atividades de restauração, como o plantio de mudas de espécies arbóreas nativas, podem auxiliar na atração de dispersores, no restabelecimento de processos ecossistêmicos e consequente modificação do ambiente (Holl *et al.* 2000; Souza & Batista 2004). O recrutamento de novas espécies vai depender de sua capacidade de chegada à área degradada e de sua sobrevivência às condições ambientais adversas e intensa competição e predação (Reid & Holl 2013). Fontes de propágulo próximas propiciam maior dispersão de propágulos e maior potencial de aumento da riqueza específica (Melo & Durigan 2007).

2.2 Serviços ecossistêmicos

Os processos ecológicos possibilitam o funcionamento do ecossistema e as interações entre as espécies e o meio. Esses processos são a base para a geração dos serviços ecossistêmicos que são ditos os benefícios que os seres humanos obtém dos ecossistemas (MA 2005). Eles podem ser também definidos como as contribuições diretas e indiretas dos ecossistemas para o bem estar humano (TEEB 2010). A classificação mais utilizada para tratar dos serviços ecossistêmicos é aquela sugerida pelo *Millenium Ecosystem Assessment* (MA 2005), que divide os serviços em quatro categorias principais: serviços de provisão, de regulação, serviços culturais e de suporte. Os serviços de provisão são aqueles que propiciam uso direto dos produtos oriundos da natureza; eles geram recursos alimentícios, medicinais e ornamentais, tais como água, comida, madeira, fibras, recursos genéticos e essências medicinais. Os serviços de regulação são aqueles obtidos através da regulação dos processos ecossistêmicos e manutenção das condições atmosféricas, hídricas e do solo, bem como as interações tróficas entre os organismos; eles incluem polinização, dispersão de sementes, controle de pestes, regulação do clima, manutenção da qualidade do ar, controle de processos erosivos e proteção contra enchentes. Os serviços culturais são aqueles benefícios não materiais que os seres humanos obtém dos ecossistemas, por meio de enriquecimento espiritual, desenvolvimento cognitivo, reflexão, recreação e experiências estéticas. Por fim, os serviços de suporte são aqueles necessários para a produção dos demais serviços ecossistêmicos, como produtividade primária, produção de oxigênio e formação do solo.

3. Atributos funcionais

Atributo funcional é um atributo do organismo que afeta o fitness individual ou da espécie via efeitos no crescimento, reprodução ou sobrevivência (Violle *et al.* 2007), respondendo a condições ambientais ou afetando propriedades do ecossistema (Lavorel 2013). Diferentemente da classificação taxonômica clássica, esses atributos permitem caracterizar espécies e comunidades em termos de seus atributos, organizar as espécies em grupos com funções ou respostas similares, podendo explicar simultaneamente respostas individuais das plantas a determinados fatores ambientais ou distúrbios e/ou efeitos destas sobre processos ecossistêmicos (Lavorel & Garnier 2002; Lamb 2005; Garnier *et al.* 2007). A vantagem de utilização de atributos funcionais ao invés de número de espécies ou índices de diversidade é que as características das plantas são as que realmente afetam o funcionamento do ecossistema (Diaz & Cabido 2001). Cada vez mais os atributos vêm sendo utilizados em estudos ecológicos e diversas bases de dados globais estão disponíveis com uma grande variedade de atributos funcionais (por exemplo, Kattge *et al.* 2011).

Os atributos funcionais das plantas podem ser classificados em grandes grupos de acordo com suas características morfológicas, fisiológicas e fenológicas (Perez-Harguindeguy *et al.* 2013). Os principais grupos são: os atributos foliares, dos quais podemos citar área foliar, área foliar específica (SLA), conteúdo de matéria seca foliar (LDMC), conteúdo de nitrogênio ou fósforo foliar e espessura de folha; atributos reprodutivos, como é o caso do peso de frutos, massa de semente e síndrome de dispersão; atributos de crescimento, como por exemplo altura máxima, forma de crescimento e densidade da madeira; e atributos de raiz, como comprimento de raiz e estratégia de aquisição de recursos. Esses atributos podem ainda ser divididos conforme sua resposta a mudanças ambientais (filtros ambientais ou biológicos) ou seus efeitos nos processos ecossistêmicos, o que são chamados de atributos resposta ou atributos de efeito (Lavorel & Garnier 2002). Atributos *resposta* são aqueles que se modificam de acordo com as condições ambientais, é o caso de alteração na taxa de crescimento em função dos efeitos do sombreamento ou da resposta das plantas (por exemplo, tamanho de folha) a mudanças climáticas. Atributos *efeito* são aqueles que influenciam nos processos ecológicos e funções no ecossistema, como por exemplo, atributos foliares (como conteúdo de nitrogênio foliar) influenciando taxas de decomposição. Dessa forma, no caso da utilização dos atributos funcionais em estudos ecológicos é importante estabelecer qual o objetivo do estudo, de modo a selecionar os atributos mais adequados para cada tipo de situação (Petchey & Gaston 2006). Ao mesmo tempo, determinados atributos tanto podem ser considerados pela sua resposta ao meio quanto por seu efeito no funcionamento do ecossistema. A área foliar específica, por exemplo, é um atributo que responde às mudanças nas condições ambientais de luminosidade, temperatura e precipitação e ao mesmo tempo interfere na produtividade primária do sistema (Lavorel & Garnier 2002).

Quando tratamos da restauração de ambientes degradados com o foco na recuperação da funcionalidade, os atributos de efeito são de extrema importância para verificar a influência da composição funcional nos processos ecossistêmicos. Diversos são os estudos que mostram o efeito dos atributos nos processos ecossistêmicos (Diaz & Cabido 2001; Garnier *et al.* 2004; Kazakou *et al.* 2006): a decomposição é influenciada negativamente pelo conteúdo de lignina das folhas e pelo LDMC e positivamente influenciada pelo conteúdo de nitrogênio (Freschet, Aerts & Cornelissen 2012); a fertilidade do solo é influenciada pelo LDMC e pelo conteúdo de nitrogênio foliar (Laughlin *et al.* 2015); o acúmulo de biomassa acima do solo e o sequestro de carbono podem ser preditos pelo SLA (Finegan *et al.* 2015) e pela densidade da madeira (Larjavaara & Muller-Landau 2010); e a sobrevivência de plântulas aumenta com o aumento da massa de semente (Moles & Westoby 2004).

A utilização de dados sobre atributos funcionais no nível da comunidade é feita através de índices que refletem a sua estrutura funcional, em termos de composição e diversidade. Os diferentes aspectos da composição funcional da comunidade podem ser expressos de duas formas principais: através da avaliação da variabilidade dos atributos funcionais ou através de medidas de média ou dominância dos mesmos. De forma mais específica, são utilizados índices de diversidade funcional (variabilidade) ou valores de CWM (do inglês *community weighted mean traits*; Garnier *et al.* 2004), que refletem atributos dominantes e mais representativos na comunidade (Ricotta & Moretti 2011). Há uma grande variedade de índices propostos para avaliar a diversidade funcional da comunidade, entretanto os mais usados são a entropia de Rao, riqueza funcional, redundância funcional e divergência funcional (Mason *et al.* 2005). Os índices de composição e diversidade funcional refletem respostas ecológicas diferentes: índices de diversidade funcional focam em respostas à complementariedade de nicho, enquanto valores de CWM respondem a questões relativas à teoria de razão de massa (*mass-ratio theory*, Grime 1998), que sugere que são os atributos das espécies dominantes que mais afetam os processos ecológicos e os serviços ecossistêmicos (Díaz *et al.* 2007).

Por fim, mais recentemente, atributos funcionais vêm sendo usados em estudos de regras de montagem (HilleRisLambers *et al.* 2012), em que são utilizados modelos para predizer comunidades baseados em atributos funcionais (Cadotte *et al.* 2015; Shipley *et al.* 2016). Esses modelos têm como objetivo predizer comunidades que potencializam algum atributo ou função de interesse ou que aumentam a diversidade funcional da comunidade (Laughlin *et al.* 2012). Por exemplo, se o interesse é acelerar a decomposição em um ecossistema, então deve-se focar em compor uma comunidade cujas espécies apresentem maiores valores de SLA e menores valores de LDMC, que propiciam o aumento das taxas de decomposição (Laughlin *et al.* 2010). Essa ferramenta pode ser aplicada na restauração ecológica, por meio da seleção de espécies para plantio em áreas degradadas, ou mesmo para monitorar trajetórias de desenvolvimento da vegetação e propor ações de manejo, baseado na composição funcional da área de referência (Laughlin 2014).

4. Objetivos da tese

Frente aos diversos problemas em restaurar ambientes degradados e às dificuldades inerentes em se avaliar o sucesso de ações de restauração, cada vez mais é necessária a aplicação de uma abordagem integrada, que considere tanto características e mecanismos da comunidade – estrutura da vegetação, composição de espécies e atributos funcionais – quanto do ecossistema – processos ecossistêmicos (Aerts & Honnay 2011). Assim, é possível analisar o restabelecimento das funções do ecossistema após as intervenções de restauração e sua persistência ao longo do tempo. Dessa forma, o objetivo do presente trabalho é abordar questões referentes aos processos ecológicos e atributos funcionais em áreas florestais em processo de restauração de modo a avaliar a funcionalidade desses ambientes. Os objetivos específicos da tese estão descritos em cada um dos 4 capítulos da presente tese de doutorado:

O Capítulo 1 apresenta uma caracterização geral dos principais processos ecológicos que ocorrem em ecossistemas florestais, indicando relações entre eles, modificações ao longo da sucessão e provisão de serviços ecossistêmicos; além disso, apresenta também uma análise das principais variáveis relacionadas a esses processos que são utilizadas no monitoramento de áreas em restauração florestal;

O Capítulo 2 aborda as diferenças na estrutura da vegetação, na diversidade florística e funcional, nos processos ecológicos (estoque de serapilheira, decomposição, detritivoria, regeneração natural e razão C:N da serapilheira e do solo) e na composição de espécies e de atributos funcionais entre áreas em processo de restauração e áreas de referência;

O Capítulo 3 tem como principal enfoque compreender a influência da diversidade florística e funcional, bem como da composição de atributos funcionais nos processos ecológicos (regeneração natural, estoque de serapilheira, biomassa arbórea acima do solo decomposição, detritivoria, regeneração natural e razão C:N da serapilheira e do solo) de comunidades florestais em diferentes estágios de desenvolvimento;

E, por fim, o Capítulo 4 trata da utilização de um modelo preditivo baseado em atributos funcionais para monitorar a composição funcional de áreas em processo de restauração e avaliar trajetórias sucessionais, com recomendações para manejo.

Os Capítulos 2, 3 e 4 são baseados em coletas de dados realizadas em campo, em três sítios de estudo. A seguir são apresentadas informações gerais sobre os sítios.

5. Descrição geral das áreas de estudo

Os itens abaixo apresentam a descrição geral das três áreas de estudo, Cachoeirinha, Canela e Santa Tereza, localizadas no Estado do Rio Grande do Sul (RS), onde foram conduzidos os levantamentos e experimentos de campo. São listadas características gerais do tipo florestal, das intervenções de restauração realizadas e informações gerais sobre os locais onde foram coletados os dados.

5.1 Cachoeirinha, RS

A área de estudo localizada em Cachoeirinha está situada no Parque Ambiental da empresa Souza Cruz (29°52’41” S; 51°05’48” W). A altitude é de cerca de 30 m, apresenta clima do tipo Cfa, com chuvas durante todos os meses do ano e temperatura média do mês mais quente superior a 22ºC (Peel, Finlayson & McMahon 2007). A mata onde foi realizada o estudo é uma mata ciliar, classificada como floresta estacional semi-decidual (Oliveira-Filho *et al.* 2015), localizada nas margens de um pequeno arroio (Arroio Nazário; Fig. 1). A largura da faixa ciliar é estreita, com cerca de 10-15 metros. A mata apresenta certa degradação ambiental, sendo seu estado de conservação considerado estágio médio de regeneração natural. O Parque Ambiental está localizado em uma matriz bastante antropizada, no distrito industrial do município. Além disso, os remanescentes florestais formam mosaicos com campos nativos da região, dada sua composição de espécies e estrutura (Backes 2014). Por esses motivos, não são encontrados muitos fragmentos florestais no entorno.

O plantio de restauração foi realizado há cerca de 12 anos (2001) com o objetivo de aumentar a largura da faixa ciliar, impactada por pastejo de gado (Fig. 1; Fotos 1 a 6). O plantio foi realizado com mudas nativas (cerca de 23 espécies), utilizando a estratégia de linhas de plantio e espaçamento de 2 x 2 m. Foi realizado acompanhamento silvicultural após plantio, mas não obteve-se informação sobre o seu período de duração. A lista de espécies e número de indivíduos amostrados na mata de referência e na área de restauração são apresentados na Tabela 1. Foram amostradas 51 espécies: 42 espécies na área de referência e 23 na restauração. A única espécie exótica incluída na amostragem foi *Peltophorum dubium* (canafístula), com um indivíduo apenas.

Figura 1. Imagem aérea da área de Cachoeirinha (RS) indicando as unidades amostrais onde foram coletados os dados (símbolos amarelos), separadas pelos dois tratamentos: área de referência (em verde) e área de restauração (em marrom). A linha azul indica o curso d'água (Arroio Nazário). Fonte: Google Earth.

Tabela 1. Lista de espécies, família botânica e número de indivíduos amostrados por tratamento (floresta de referência e de restauração) em Cachoeirinha, RS. Símbolo (*) indica espécie exótica da flora do Rio Grande do Sul.

Família botânica	**Espécie**	**Referência**	**Restauração**
LAMIACEAE	*Aegiphila integrifolia* (Jacq.) Moldenke	3	
SAPINDACEAE	*Allophylus edulis* (A. St.-Hil., Cambess. & A. Juss.) Radlk.	29	3
ANNONACEAE	*Annona* sp.		2

Família botânica	Espécie	Referência	Restauração
ANNONACEAE	*Annona sylvatica* A. St.-Hil.	1	
FABACEAE	*Apuleia leiocarpa* (Vogel) J.F.Macbr.		8
APOCINACEAE	*Aspidosperma australe* Müll.Arg.		1
MYRTACEAE	*Blepharocalyx salicifolius* (Kunth) O.Berg	4	
SALICACEAE	*Casearia decandra* Jacq.	1	
SALICACEAE	*Casearia sylvestris* Sw.	18	
MELIACEAE	*Cedrela fissilis* Vell.	3	
ULMACEAE	*Celtis iguanaea* (Jacq.) Sarg.	1	2
SAPOTACEAE	*Chrysophyllum marginatum* (Hook. & Arn.) Radlk.	7	
BORAGINACEAE	*Cordia americana* (L.) Gottschling & J.S. Mill.	2	1
SAPINDACEAE	*Cupania vernalis* Cambess.	2	
ERYTHROXYLACEAE	*Erythroxylum argentinum* O.E. Schultz	6	1
ERYTHROXYLACEAE	*Erythroxylum deciduum* A.St.-Hil.	3	14
MYRTACEAE	*Eugenia hyemalis* Cambess.	3	
MYRTACEAE	*Eugenia uniflora* L.		2
MYRTACEAE	*Eugenia verticillata* (Vell.) Angely	1	
RUBIACEAE	*Faramea montevidensis* (Cham. & Schltdl.) DC	1	
MORACEAE	*Ficus luschnathiana* (Miq.) Miq.	1	
FABACEAE	*Inga marginata* Willd.		13
FABACEAE	*Inga vera* Willd.		2
BIGNONIACEAE	*Jacaranda micrantha* Cham.		3
ANACARDIACEAE	*Lithraea brasiliensis* Marchand	1	
MALVACEAE	*Luehea divaricata* Mart. & Zucc.	8	6
SAPINDACEAE	*Matayba elaeagnoides* Radlk	2	
MELASTOMATACEAE	*Miconia sellowiana* Naudin	2	
FABACEAE	*Mimosa bimucronata* (DC.) Kuntze	5	5
MYRTACEAE	*Myrcia glabra* (O. Berg) D. Legrand	3	
MYRTACEAE	*Myrcia multiflora* (Lam.) DC.	1	
MYRTACEAE	*Myrcia palustris* DC.	1	
PRIMULACEAE	*Myrsine coriacea* R.Br.	7	4
PRIMULACEAE	*Myrsine lorentziana* (Mez) Arechav	1	
PRIMULACEAE	*Myrsine umbellata* Mart.	1	
LAURACEAE	*Nectandra grandiflora* Nees	3	
LAURACEAE	*Ocotea puberula* (Rich.) Nees	8	2
LAURACEAE	*Ocotea pulchella* (Nees) Mez	2	
FABACEAE	*Parapiptadenia rigida* (Benth.) Brenan		6
FABACEAE	*Peltophorum dubium* (Spreng.) Taub. *	1	
ROSACEAE	*Prunus myrtifolia* (L.) Urb.	13	2
MYRTACEAE	*Psidium cattleyanum* Sabine		44
ANACARDIACEAE	*Schinus terebinthifolius* Raddi	1	49
EUPHORBIACEAE	*Sebastiania brasiliensis* Spreng.	2	
EUPHORBIACEAE	*Sebastiania serrata* (Baill. Ex Müll. Arg.) Müll. Arg.	165	1
MORACEAE	*Sorocea bonplandii* (Baill.) W.C. Burger, Lanj. & Wess. Boer	1	
ARECACEAE	*Syagrus romanzoffiana* (Cham.) Glassman	2	
ULMACEAE	*Trema micrantha* (L.) Blume	1	
LAMIACEAE	*Vitex megapotamica* (Spreng.) Moldenke	2	7
RUTACEAE	*Zanthoxylum fagara* (L.) Sarg.	9	1
RUTACEAE	*Zanthoxylum rhoifolium* Lam.	10	

Fotos 1 a 6. Aspecto geral da área de restauração (1) e da área de referência (2) na localidade de Cachoeirinha, RS; coleta de serapilheira na área de restauração (3); coleta de serapilheira e instalação do experimento de detritivoria (4); *bait-laminas* e ganchos utilizados para identificar o local da instalação (5); experimento de *bait-laminas* instalado no solo (6).

Foi observada a atividade de animais de pequeno porte no local, identificada através de fezes encontradas e também de predação nos equipamentos de identificação dos experimentos (tais como bandeirolas no experimento de *bait-laminas*). Foram verificadas diferenças de temperatura no interior das fisionomias, sendo a área de restauração mais quente e com solo mais seco que a área de referência. Além disso, a área de restauração apresentou menor área basal, altura da mata e densidade de indivíduos do que a área de referência.

Em estudo realizado nessa mesma área, Fonseca (2013) verificou uma maior semelhança entre o sub-bosque da área de restauração e o dossel da área de referência. Isso indica que houve colonização de espécies oriundas da mata de referência para a área em processo de restauração.

5.2 Canela, RS

A área de estudo situada em Canela está localizada no horto florestal da Companhia Estadual de Energia Elétrica (CEEE) (29°22’43” S; 50°43’50” W), nas proximidades das represas de Canastra e Bugres. A altitude é de cerca de 612 m, com clima do tipo Cfa, classificado como subtropical úmido com verão quente (Peel *et al.* 2007). A região é caracterizada por chuvas bem distribuídas durante o ano e temperatura média do mês mais quente superior a 22ºC (Peel *et al.* 2007). A mata onde foi realizada o estudo é classificada como floresta estacional semi-decidual, mas dada a proximidade com a Floresta com Araucária (distribuída em altitudes um pouco mais elevadas), há influência de espécies que ocorrem nesta formação (Oliveira-Filho *et al.* 2015). A matriz florestal do entorno é bastante favorável, sendo observados diversos fragmentos florestais conservados em maior ou menor grau no entorno. A floresta considerada como floresta de referência pode ser classificada como estágio avançado de regeneração natural.

O plantio de restauração foi realizado há cerca de 8 anos (2007) em área onde antes havia plantio de eucalipto (Fig. 2; Fotos 7 a 12). No ano de 2006 os eucaliptos foram removidos e no ano seguinte iniciou-se o plantio de mudas nativas para recuperação da área (Boeni 2016). O plantio foi realizado com mudas nativas (cerca de 34 espécies), utilizando a estratégia de linhas de plantio e espaçamento 2,5 x 2,5 metros. Não foram obtidos dados a respeito do acompanhamento silvicultural após o plantio. A lista de espécies e o número de indivíduos amostrados em cada tratamento (área de restauração e mata de referência) são apresentados na Tabela 2. A amostragem resultou na identificação de 72 espécies (incluindo espécies indeterminadas): 47 na floresta de referência e 55 na área de restauração. Foram identificadas 5 espécies exóticas (*Citrus sinensis*, *Eucalyptus* sp., *Hovenia dulcis*, *Peltophorum dubium* e *Tecoma stans*), representando 7% do total de indivíduos amostrados.

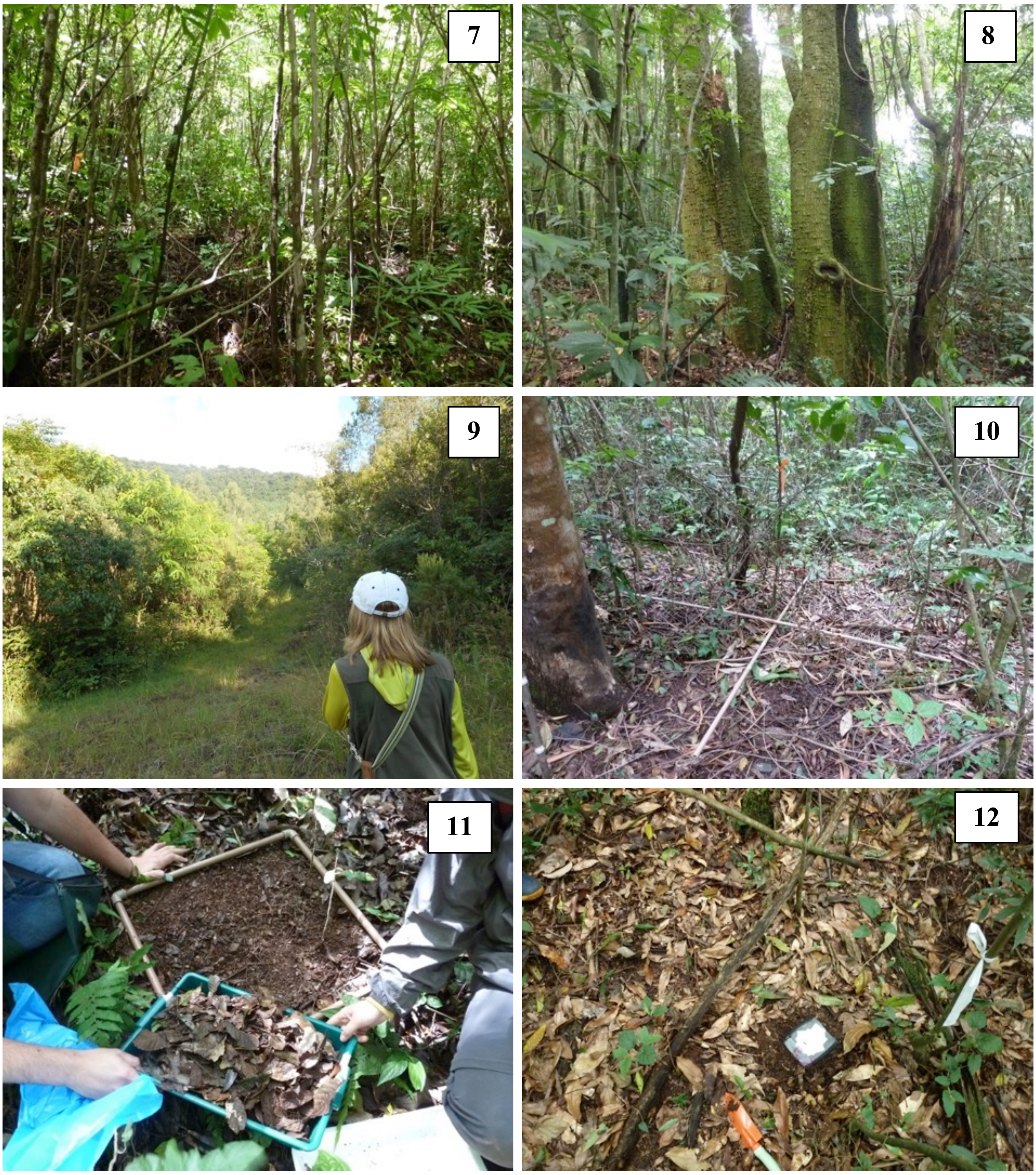
Figura 2. Imagem aérea da área de Canela (RS) indicando as unidades amostrais onde foram coletados os dados (símbolos amarelos), separadas pelos dois tratamentos: área de referência (em verde) e área de restauração (em marrom). A hachura cinza indica o local onde anteriormente havia os plantios de eucalipto. Fonte: Google Earth.

Foi observada a atividade de animais de médio e grande porte no local, identificada através de fuçadas e revolvimento do solo (possivelmente realizada por javalis ou porcos selvagens). Foi identificada também a presença de bugios, através de vocalização e observação direta dos animais. As diferenças de temperatura e umidade também foram identificadas entre os tratamentos, sendo os locais no interior da área de restauração mais secos e quentes do que a floresta de referência. A área de restauração apresentou menor área basal e altura, mas maior densidade de indivíduos que a área de referência.

Tabela 2. Lista de espécies, família botânica e número de indivíduos amostrados por tratamento (floresta de referência e de restauração) em Canela, RS. Símbolo (*) indica espécie exótica da flora do Rio Grande do Sul.

Família botânica	Espécie	Referência	Restauração
EUPHORBIACEAE	*Actinostemon concolor* (Spreng.) Müll.Arg.	1	
EUPHORBIACEAE	*Alchornea triplinervia* (Spreng.) Müll.Arg.	3	3
SAPINDACEAE	*Allophylus edulis* (A. St.-Hil., Cambess. & A. Juss.) Radlk.		2
ANNONACEAE	*Annona rugulosa* (Schltdl.) H.Rainer	2	
FABACEAE	*Ateleia glazioviana* Baill.		7
ASTERACEAE	*Baccharis semiserrata* DC.		19
SALICACEAE	*Banara parviflora* (A. Gray) Benth.		1
FABACEAE	*Bauhinia forficata* Link		4
MYRTACEAE	*Blepharocalyx salicifolius* (Kunth) O.Berg	8	3
URTICACEAE	*Boehmeria caudata* Sw.	6	4
MELIACEAE	*Cabralea canjerana* (Vell.) Mart.	4	2
MYRTACEAE	*Campomanesia xanthocarpa* O.Berg	7	3
SALICACEAE	*Casearia decandra* Jacq.	2	
SALICACEAE	*Casearia sylvestris* Sw.	17	7
MELIACEAE	*Cedrela fissilis* Vell.		1
ULMACEAE	*Celtis iguanaea* (Jacq.) Sarg.	2	
SOLANACEAE	*Cestrum intermedium* Sendtn.	2	
SAPOTACEAE	*Chrysophyllum marginatum* (Hook. & Arn.) Radlk.	1	1
VERBENACEAE	*Citharexylum myrianthum* Cham.	4	1
VERBENACEAE	*Citharexylum solanaceum* Cham.		2
RUTACEAE	*Citrus sinensis* (Linn.) Osbeck *	3	
BORAGINACEAE	*Cordia americana* (L.) Gottschling & J.S. Mill.		1
SAPINDACEAE	*Cupania vernalis* Cambess.	65	17
FABACEAE	*Dalbergia frutescens* (Vell.) Britton	1	
ASTERACEAE	*Dasyphyllum spinescens* (Less.) Cabrera		3

Família botânica	**Espécie**	**Referência**	**Restauração**
EBENACEAE	*Diospyros inconstans* Jacq.	3	1
FABACEAE	*Enterolobium contortisiliquum* (Vell.) Morong		2
FABACEAE	*Erythrina falcata* Benth.	4	3
ERYTHROXYLACEAE	*Erythroxylum argentinum* O.E. Schultz	2	3
MYRTACEAE	*Eucalyptus* sp. *		10
MYRTACEAE	*Eugenia ramboi* D.Legrand	4	2
MYRTACEAE	*Eugenia rostrifolia* D.Legrand	1	1
MORACEAE	*Ficus adhatodifolia* Schott ex Spreng.		1
RHAMNACEAE	*Hovenia dulcis* Thunb. *	3	8
-	Indeterminada 1	1	
-	Indeterminada 2	1	
-	Indeterminada 3	1	
-	Indeterminada 4	1	
-	Indeterminada 5 (Fabaceae)		1
-	Indeterminada 6 (Rubiaceae)		1
FABACEAE	*Inga marginata* Willd.	1	46
FABACEAE	*Inga sessilis* (Vell.) Mart.	3	28
MALVACEAE	*Luehea divaricata* Mart. & Zucc.	4	9
FABACEAE	*Machaerium paraguariense* Hassl.	20	3
FABACEAE	*Machaerium stipitatum* (DC.) Vogel	9	2
SAPINDACEAE	*Matayba elaeagnoides* Radlk	5	
MYRTACEAE	*Myrcianthes gigantea* (D. Legrand) D. Legrand	1	
PRIMULACEAE	*Myrsine coriacea* R.Br.		29
PRIMULACEAE	*Myrsine lorentziana* (Mez) Arechav	1	2
PRIMULACEAE	*Myrsine umbellata* Mart.	2	9
LAURACEAE	*Nectandra megapotamica* (Spreng.) Mez	59	26
LAURACEAE	*Ocotea puberula* (Rich.) Nees	2	10
FABACEAE	*Parapiptadenia rigida* (Benth.) Brenan	6	10
FABACEAE	*Peltophorum dubium* (Spreng.) Taub. *		4
PHYTOLACCACEAE	*Phytolacca dioica* L.	1	
NYCTAGINACEAE	*Pisonia zapallo* Griseb.	5	
RUBIACEAE	*Psychotria brachyceras* Müll. Arg.	1	
QUILLAJACEAE	*Quillaja brasiliensis* (A.St.-Hil. & Tul.) Mart.		1
EUPHORBIACEAE	*Sapium glandulosum* (L.) Morong	1	2
ANACARDIACEAE	*Schinus polygamus* (Cav.) Cabrera		3
ANACARDIACEAE	*Schinus terebinthifolius* Raddi		20
SOLANACEAE	*Solanum mauritianum* Scop.		8
SOLANACEAE	*Solanum pseudoquina* A. St.-Hil.		5
STYRACACEAE	*Styrax leprosus* Hook. & Arn.		1
BIGNONIACEAE	*Tecoma stans* (L.) Juss. ex Kunth *		21
ULMACEAE	*Trema micrantha* (L.) Blume	8	48
MELIACEAE	*Trichilia claussenii* C.DC.	2	4
URTICACEAE	*Urera baccifera* (L.) Gaudich.	8	6
SALICACEAE	*Xylosma pseudosalzmanii* Sleumer	1	1
RUTACEAE	*Zanthoxylum petiolare* A. St.-Hil. & Tul.		2
RUTACEAE	*Zanthoxylum rhoifolium* Lam.	1	1



Fotos 7 a 12. Aspecto geral da área de restauração (7) e da área de referência (8) na localidade de Canela, RS; vista externa da área de restauração (9); levantamento da regeneração na área de referência (10); coleta de serapilheira na área de referência (11); e instalação dos *litterbags* no solo (12).

Em estudo realizado nas mesmas áreas de restauração (Boeni 2016), mas com objetivo de comparar esses locais com locais de remoção de eucalipto, porém sem plantio de mudas, foi encontrada alta similaridade florística entre as duas áreas (com e sem plantios). Isso indica o potencial da regeneração natural em promover mudanças em áreas degradadas. Por outro lado, em outro estudo realizado no local (Schüler 2016), foi evidenciado que as áreas de restauração não diferiram da floresta de referência quanto à riqueza e densidade de indivíduos regenerantes, mas diferiram em termos de composição de espécies. Além disso, a abertura de dossel, estimada através de fotos hemisféricas, não diferiu entre as áreas de restauração e a floresta de referência (Schüler 2016).

5.3 Santa Tereza, RS

A área de estudo situada em Santa Tereza (29°09’27” S; 51°41’45” W) está localizada em área particular, na qual o objetivo do proprietário é a preservação ambiental. A altitude é de cerca de 240 m e o clima é do tipo Cfa, apresentando chuvas bem distribuídas durante o ano e alta variação de temperatura entre os meses frios e quentes (Peel *et al.* 2007). A mata onde foi realizado o estudo é classificada como floresta estacional semi-decidual (Oliveira-Filho *et al.* 2015) e pode ser classificada como estágio médio a avançado de regeneração. A vegetação do entorno é razoavelmente bem preservada, sendo observados inúmeros fragmentos florestais conservados em meio a áreas de produção agrícola (viticultura e plantio de eucalipto).

O plantio de restauração foi realizado há cerca de 10 anos (2006) em área onde era realizado o plantio de uvas (viticultura) (Fig. 3; Fotos 13 a 16). O plantio foi realizado com mudas nativas (cerca de 21 espécies), utilizando a estratégia de linhas de plantio e espaçamento 2 x 2 metros. Não foram obtidos dados a respeito das espécies efetivamente plantadas, tampouco do monitoramento após o plantio. A lista de espécies e o número de indivíduos amostrados em cada tratamento (área de restauração e mata de referência) são apresentados na Tabela 3. A amostragem resultou na identificação de 44 espécies (incluindo espécies indeterminadas): 35 na floresta de referência e 20 na área de restauração. Foram identificadas 6 espécies exóticas (*Citrus* sp., *Eriobotrya japonica*, *Hovenia dulcis*, *Morus nigra*, *Peltophorum dubium* e *Tecoma stans*), representando 3% do total de indivíduos amostrados.

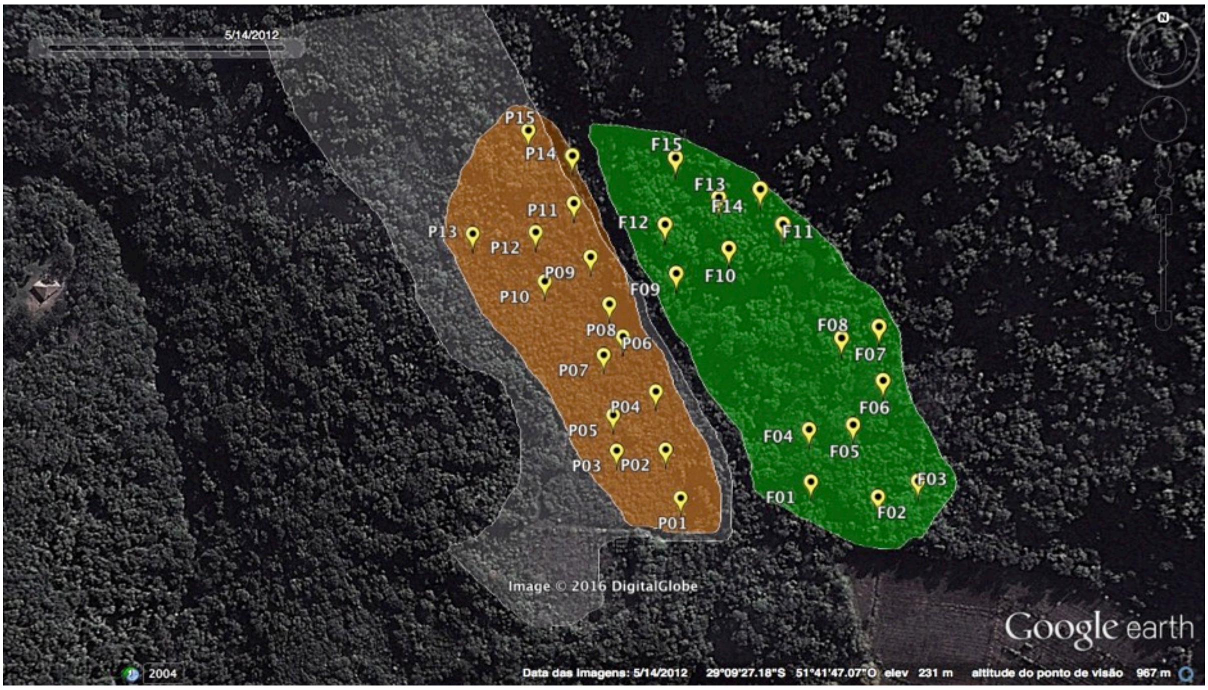


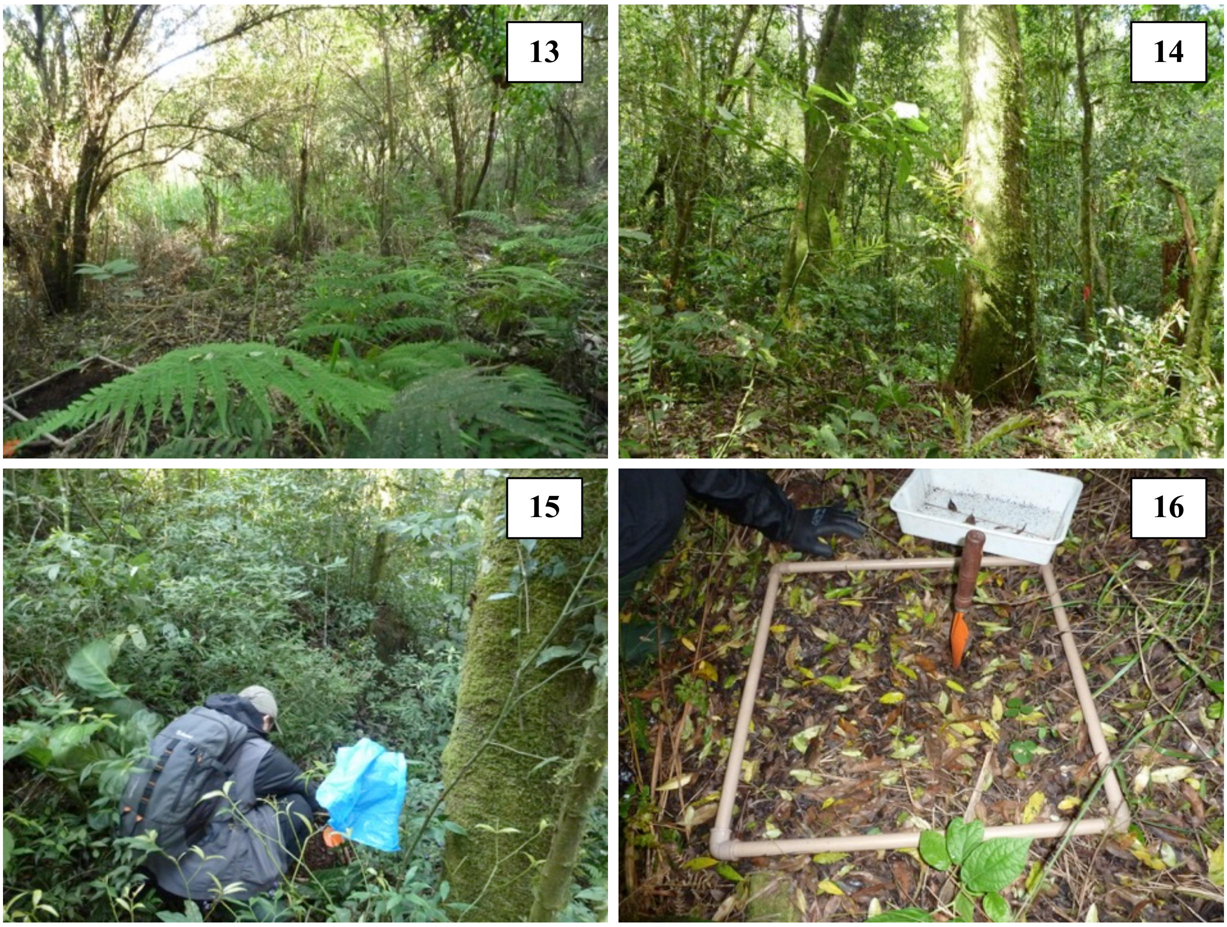
Figura 3. Imagem aérea da área de Santa Tereza (RS) indicando as unidades amostrais onde foram coletados os dados (símbolos amarelos), separadas pelos dois tratamentos: área de referência (em verde) e área de restauração (em marrom). A hachura cinza indica o local onde anteriormente havia o cultivo de uva. Fonte: Google Earth.

Bem como nas demais áreas de estudo, foram identificadas em campo diferenças de temperatura e umidade entre os tratamentos, sendo os locais no interior da floresta mais úmidos e com temperaturas mais amenas do que nas áreas de restauração. Além disso, foi verificada presença de gramíneas invasoras (por exemplo, braquiária), especialmente nas bordas da área de restauração, próximo à trilha. A área de restauração apresentou menor área basal e altura, entretanto a densidade de indivíduos foi semelhante à área de referência.

Tabela 3. Lista de espécies, família botânica e número de indivíduos amostrados por tratamento (floresta de referência e de restauração) em Santa Tereza, RS. Símbolo (*) indica espécie exótica da flora do Rio Grande do Sul.

Família botânica	Espécie	Referência	Restauração
SAPINDACEAE	*Allophylus edulis* (A. St.-Hil., Cambess. & A. Juss.) Radlk.	4	4
SAPINDACEAE	*Allophylus guaraniticus* (A. St.-Hil.) Radlk.	2	
ARAUCARIACEAE	*Araucaria angustifolia* (Bertol.) Kuntze		8
SALICACEAE	*Banara tomentosa* Clos	6	
FABACEAE	*Bauhinia forficata* Link	1	
MYRTACEAE	*Campomanesia xanthocarpa* O.Berg	1	
SALICACEAE	*Casearia sylvestris* Sw.	13	1
MELIACEAE	*Cedrela fissilis* Vell.	9	4
RUTACEAE	*Citrus sp.* *	2	
BORAGINACEAE	*Cordia americana* (L.) Gottschling & J.S. Mill.	2	
BORAGINACEAE	*Cordia trichotoma* (Vell.) Arrab. ex Steud.		1
SAPINDACEAE	*Cupania vernalis* Cambess.	14	1
ROSACEAE	*Eriobotrya japonica* (Thunb.) Lindl. *	1	
ESCALLONIACEAE	*Escallonia bifida* Link & Otto		176
MYRTACEAE	*Eugenia uniflora* L.	4	
MYRTACEAE	*Eugenia uruguayensis* Cambess.	1	
BIGNONIACEAE	*Handroanthus albus* (Cham.) Mattos		2
RHAMNACEAE	*Hovenia dulcis* Thunb. *	6	
-	Indeterminada (sem folhas)	1	
-	Indeterminada #01	1	
-	Indeterminada #02	1	
-	Indeterminada #03	1	
-	Indeterminada #05 (sem folhas)	1	
-	Indeterminada #08	1	
-	Indeterminada #09	1	
FABACEAE	*Inga marginata* Willd.	2	
FABACEAE	*Lonchocarpus campestris* Mart. ex Benth.	15	1
MALVACEAE	*Luehea divaricata* Mart. & Zucc.	19	14
FABACEAE	*Machaerium paraguariense* Hassl.		11
FABACEAE	*Machaerium stipitatum* (DC.) Vogel		1
MORACEAE	*Morus nigra* Linn. *		3
PRIMULACEAE	*Myrsine coriacea* R.Br.	1	9
PRIMULACEAE	*Myrsine umbellata* Mart.	9	5
LAURACEAE	*Nectandra megapotamica* (Spreng.) Mez	20	
LAURACEAE	*Ocotea porosa* (Nees) Barroso	3	
LAURACEAE	*Ocotea puberula* (Rich.) Nees	1	4

Família botânica	Espécie	Referência	Restauração
FABACEAE	*Parapiptadenia rigida* (Benth.) Brenan	6	7
FABACEAE	*Peltophorum dubium* (Spreng.) Taub. *		1
ROSACEAE	*Prunus myrtifolia* (L.) Urb.	1	1
MORACEAE	*Sorocea bonplandii* (Baill.) W.C. Burger, Lanj. & Wess. Boer	3	
BIGNONIACEAE	*Tecoma stans* (L.) Juss. ex Kunth *		5
MELIACEAE	*Trichilia claussenii* C.DC.	42	
MELIACEAE	*Trichilia elegans* A. Juss.	21	
SALICACEAE	*Xylosma pseudosalzmanii* Sleumer	1	



Fotos 13 a 16. Aspecto geral da área de restauração (13) e da área de referência (14) na localidade de Santa Tereza, RS; sub-bosque denso na área de referência (15); coleta de serapilheira na área de restauração (16).

Em estudo realizado no local (Schüler 2016), foram encontradas diferenças tanto para riqueza quanto para densidade de indivíduos regenerantes entre a floresta e a restauração: as áreas de restauração apresentaram valores inferiores para os dois parâmetros avaliados. A composição de espécies regenerantes também diferiu entre os tratamentos, sendo mais homogênea na floresta quando comparada à restauração. Além disso, a abertura de dossel, estimada através de fotos hemisféricas, diferiu entre os tratamentos sendo 30% maior nas áreas de restauração (Schüler 2016).

CAPÍTULO 1

Incluindo processos ecológicos e funcionamento do ecossistema no monitoramento de florestas em restauração

Including ecological processes and ecosystem functioning in the monitoring of forest restoration

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As citações e referências bibliográficas deste capítulo seguem as normas da revista *Oecologia*. Figuras e tabelas foram inseridas no corpo do texto de modo a facilitar a leitura.

Including ecological processes and ecosystem functioning in the monitoring of forest restoration

Abstract

Restoration of forest cover is important for the recovery of ecosystem functioning, through the reestablishment of ecological processes. These processes underlie ecosystem functions and deliver vital ecosystem services to humans. Thus monitoring ecological processes in these former degraded sites is essential to the proper evaluation of ecosystem functioning. Here we describe how functions and processes are characterized in forest ecosystems, how they relate to one another and change along succession and discuss the ecosystem services that are a direct result of these functions. By also performing a literature survey we provide an assessment of the field measures used to monitor and evaluate ecosystem functioning in forest areas undergoing restoration. We also gathered information on the restoration project and on the effects of restoration on each ecological process evaluated. As a result of the literature survey, nutrient cycling was the most assessed function, followed by ecosystem resilience, productivity, water relations and biotic interactions. We found that frequent measures in restoration sites increased as restoration aged and that space-for-time substitution was a frequent strategy for evaluating changes over time. Finally, positive effects of restoration increased with time since the start of the restoration, indicating that ecological processes may take longer to recover. Restoration interventions promote changes on ecological processes that are important for ecosystem functionality. Monitoring of these sites should be performed over a longer period so that restoration success is properly assessed.

Keywords: ecosystem function; ecosystem services; functionality; nutrient cycling; regeneration.

1.1 Introduction

Forests undergoing restoration are former degraded sites that required (or still require) human interventions in order to re-establish their ecological integrity. Degraded sites do not provide the same ecological functions that mature forests do and can actually contribute to environmental problems, such as erosion and flooding, not to mention global changes to climate (Díaz et al. 2006). Further, degradation can imply in a change of a forest site from carbon sink to carbon source and thus contribute to increasing emissions of carbon dioxide to the atmosphere (Clark 2004). The return of native vegetation cover, on the other hand, is important for many different purposes, from plant and animal conservation to direct sustainable use and indirect human benefits (which are usually taken from granted). Recovering degraded sites can increase values of biodiversity, positively affecting ecosystem functioning (Díaz et al. 2006). Restoration can be a cost-effective practice that promotes ecosystem conservation, but also human well-being (Birch et al. 2010), agricultural production and socio-economic prosperity (Ghaley et al. 2014).

Forests provide essential ecosystem services (i.e. the benefits provided by ecosystems to humans; MA 2005) that reflect the functions and the ecological processes that occur in these systems. Ecological processes are important because they can modify environmental conditions and resource availability, maintaining biodiversity and promoting biotic interactions. They underlie ecosystem functions and act at different levels of ecosystem's organization, generating sustainability in the long term, also delivering vital ecosystem services. Functions related to the maintenance of essential ecological processes and life support systems, refuge and reproduction habitat to wild plants and animal species, and supply of natural resources (De Groot et al. 2002), thus offering different set of goods and services to humans (regulation, provision, supporting and cultural services). For example: pollination, which assures the reproduction of different crops and wild species, is provided by insects and birds that often rely on natural vegetation; productivity and biomass accumulation promote forest growth by removing carbon from the atmosphere, thus supplying raw materials such as timber and fiber (De Groot et al. 2002).

Since the recovery of ecosystem functioning in areas undergoing restoration is a complex and long term task, it depends on different components of the system that should be monitored. Traditionally, a strong focus in forest restoration monitoring had been on tree species diversity and vegetation structure. Under this approach, common measures of restoration success include changes in vegetation structure (e.g. increase in height and basal area) and species richness. However, more recently, there has been important progress moving beyond the vegetation perspective, and many studies now consider a broader range of ecological and ecosystem processes (Ruiz-Jaen and Aide 2005; Wortley et al. 2013; Kollmann et al. 2016). Changes in vegetation structure do not necessarily imply in a modification in ecosystem functionality (Cortina et al. 2006; Matzek et al. 2016), so direct and multiple measures should be taken in order to determine the overall functioning in these sites (Meyer et al. 2015). Despite – or maybe because of – these recent advances, the search for the best indicators of restoration success is subject to strong debate (Reid 2015; Suganuma and Durigan 2015; Brancalion and Holl 2016). Certainly the choice of different parameters for evaluation also depends on the environmental context and restoration objective. Ecological processes are influenced by ecosystem type and by the environmental characteristics acting on it (Norden et al. 2015). Thus, determining reference values based on the evaluation of the target ecosystem is important to determine whether observed measures are performing well according to the reference condition. Also, it is important to note that some ecological processes may take longer to recover and that changes along succession are expected (Guariguata and Ostertag 2001; Benayas et al. 2009). This reinforces the need for long time monitoring, in order to evaluate successional trajectories and suggest management actions if necessary.

The objective of this study is to characterize the main ecological processes in forest ecosystems, describing how they change along sucession, how different processes relate to one another and discuss the ecosystem services that are a direct result of them. To highlight the importance of these processes for the restoration of degraded forest sites, we also provide an assessment of the ecological processes being monitored in restoration sites. For this aim, we performed a search in the literature to identify which and how ecological processes are assessed in terrestrial forest restoration studies. We explored these results and described the type of function assessed, characteristics from the restored site and the results obtained from the study. This search allows us to describe the types of measures used in the field and how they aid at assessing the recovery of forest ecosystem functioning. Our focus is to discuss what ecological theory describes for each ecological process, also suggesting important ecological processes that should be evaluated in areas undergoing restoration. This study emphasizes the importance of assessing ecological processes in forest restoration, moving beyond the evaluation of simple biodiversity and structural components.

1.2 Material and methods

To characterize the different ecological processes that occur in forest ecosystems, we grouped processes in five function categories (a modified version of Kollmann et al. 2016): nutrient cycling, productivity, biotic interactions, ecosystem resilience and water relations. We described each function category based on the ecological theory and focused on the importance of measuing each processes in the recovery of restoration sites.

With the aim of identifying the field measures used to monitor ecological processes in sites undergoing restoration, we performed a literature search. We ran the search on ISI

Web of Science in August 2015 (an updated it in July 2016) using the following search term combination: (restor* OR recover*) AND forest* AND ecosystem AND (process* OR function*) AND ecolog*. Results were refined by area (Environmental Science Ecology, Forestry, Geology, Biodiversity Conservation and Plant Sciences) and we considered only research articles published in the last 30 years (starting from 1985). From this search we obtained 696 results. We screened the title and abstract from these papers and considered valid only the ones that met the selection criteria: studies that focused on terrestrial forest types (excluding forests strongly influenced by water regimes like bogs, wetlands and mangroves), that focus on restoration (excluding natural recovery – succession, except if the study was clearly stated that it was passive restoration), that were field-based studies (no review, modeling or remote sensing studies were included) and finally that had at least one ecological process quantified (excluding those that used only measures of vegetation structure, e.g. plant cover, height, diversity). Our final list included 106 papers that met the selection criteria. All papers were fully read and we extracted information related to the study site (climate domain, country, land history), restoration characteristics (restoration type, inclusion of reference site, years since start of restoration, frequency of measurements), ecological process evaluated (including the variables measured) and results from the study stating the effect of the intervention (restoration) on the processes evaluated (Table 1.2). We divided this last topic (results) in broad categories stating the restoration effect on the ecological process: similar to the characteristics found in the reference ecosystem, positive effect, no effect, negative effect and unclear (Table 1.2). Climate domains were classified according to (FAO 2012).

Table 1.1. Table of functions used to group different ecological processes. Function categories follow Kollmann et al. (2016). The number of studies for each category are shown in parenthesis.

Function category	**Ecological process**	**Variable measured in the analyzed studies**
Nutrient cycling (47)	nutrient availability and dynamics (24)	soil C, N, P or organic matter pools
	soil biotic processes (9)	litter decomposition, soil biota activity (including by fungi/microbes)
Productivity (27)	plant biomass rates (biomass production) (6)	increment measures: litterfall, plant (biomass) growth rate, primary productivity, litter production
	plant biomass stock (storage and dynamics) (20)	aboveground biomass (AGB), belowground biomass (BGB), litter stock
Biotic interactions (19)	dispersal (4)	seed removal, fauna activity
	facilitation (2)	plant survival/growth
	herbivory (2)	herbivory
	mutualism (3)	ant-plant interaction (for sugar)
	pollination (6)	flower availability/visitation
	predation (1)	animal foraging behavior
	both pollination and herbivory (1)	-
Ecosystem resilience (35)	regeneration (35)	seedling density/diversity, seedling recruitment, seed bank/density
Water relations (25)	infiltration (5)	infiltration
	soil moisture (18)	soil moisture/humidity (water content)
	surface runoff (2)	surface runoff

Table 1.2. Information extracted from each study included in our search.

Sections	**Parameters**	**Categories**	**Observations**
General information	Year	From 1985 to 2016	Year of publication.
Study site	Climate domain	Tropical, Subtropical, Temperate or Boreal	Climate domains were classified according to FAO (2012). "Subtropical" includes Mediterranean climate.
	Country	(open)	Country where data was collected.
	Land use history	farming (agriculture/grazing), logging, mining, fire, fire suppression	land use type or disturbance prior to restoration interventions; fire=wildfires or human-caused fire events; fire exclusion= in sites where fire is a natural event.
Restoration	Restoration type	active or passive	-
	Restoration action	planting; seeding; fencing; thinning/burning; management; none	restoration action: tree planting; seeding; fencing; management=thinning/burning; none=natural succession
	Restoration age (maximum time)	up to 5 years; 5 to 15 years; more than 15 years	time since start of restoration (age of site at the time of measurement)
	Frequency of measurement	single or multiple measures	frequency of evaluations in time, also includes space-for-time substitution
	Reference site	yes or no	presence of reference site
Ecological function/ process evaluated	Function category	Nutrient cycling, productivity, biotic interactions, ecosystem resilience or water relations	-
	Ecosystem process	see Table 1.1	-
	Variable measured	(open)	Specific variable measured in the study.

Sections	**Parameters**	**Categories**	**Observations**
	Results (restoration effect on the process)	(1) similar to reference; (2) positive; (3) no effect; (4) negative; (5) unclear	Possible results: (1) similar to reference: value of a given process is similar to the reference ecosystem; (2) positive: value of a given process increases during ecosystem recovery OR restoration practice improves process OR value of process is lower in restoration when compared to reference; (3) no effect: process does not change after restoration interventions; (4) negative: value of a given process decreases during recovery OR process is higher in restoration than in reference (but always in a negative way); (5) unclear: general conclusions are unclear, not possible to generalize.

1.3 Results

Results of the literature search found a total of 106 papers that met the criteria and were included in the present evaluation encompassing tropical (37 papers), subtropical (43), temperate (25) and boreal (1) climate regions (Table S1.1). Most papers focused on tropical and subtropical ecosystems (75%) and the countries that were most focused on were United States (26), Brazil (20), Australia (13) and China (12). Most papers reported active restoration (91%) and mainly tree planting (58%) as restoration action. Reference sites as a target to restoration were included in 42% of the studies. We found more single measurements on young restoration sites (up to 5 years since the start of restoration) than in older sites (more than 15 years; 34 and 20 studies respectively). In contrast, multiple measurements had the opposite pattern: few in young sites (4) and 6-times more in older sites (25).

Among the 106 valid papers, we found information on a total of 153 ecosystem processes (41 studies had more than one process measured; Table 1.1). Nutrient cycling was the most frequent function evaluated (47), followed by ecosystem resilience (35), productivity (27), water relations (25) and biotic interactions (19). The ecological processes and the variables used to assess each function were: nutrient availability (soil carbon, nitrogen, phosphorus or organic matter pools) and soil biotic processes (decomposition, fungi diversity and microbial community) for nutrient cycling; biomass rates (litter production, litterfall, growth rate) and biomass stock (litter stock, aboveground and belowground biomass) for productivity; dispersal, facilitation, herbivory, mutualism, pollination and predation for biotic interactions; regeneration (seedling density/diversity, seed bank) for ecosystem resilience; and soil moisture, infiltration and surface runoff for water relations (Table 1.1). Many of the above listed measures provide only a snapshot of a specific condition and not an evaluation of changes in time (e.g. nutrient pools or biomass stock), however in almost half of the papers that included these measures, the assessment was performed at multiple times. It is important to note that space-for-time substitution was an important tool for the evaluation of changes in time: from the 37 papers that evaluated multiple ages, 28 studies (76%) showed this type of substitution.

Results from the effect of the restoration on the ecological processes evaluated showed that positive effects increased with time since start of the restoration: we found more “positive” and “similar to reference” results in older sites (more than 15 years since the start of the restoration; Fig. 1.1). Also “no effect” of restoration interventions was more frequent in younger sites (up to 5 years since the start of the restoration). For all processes evaluated, the number of papers showing “positive” results was higher after 15 years since the start of the restoration, and “no effect” was higher in sites up to 5 years. The results were considered inconclusive or unclear in 32 out of 153 times. Negative results of restoration interventions were found in 8 papers and relate to detrimental effects of salvage logging on regeneration, afforestation on soil moisture, and decreased fungi richness in restoration treatments. It is important to note that negative results are often not published in the scientific literature, which might be underestimating the number of papers in this category.

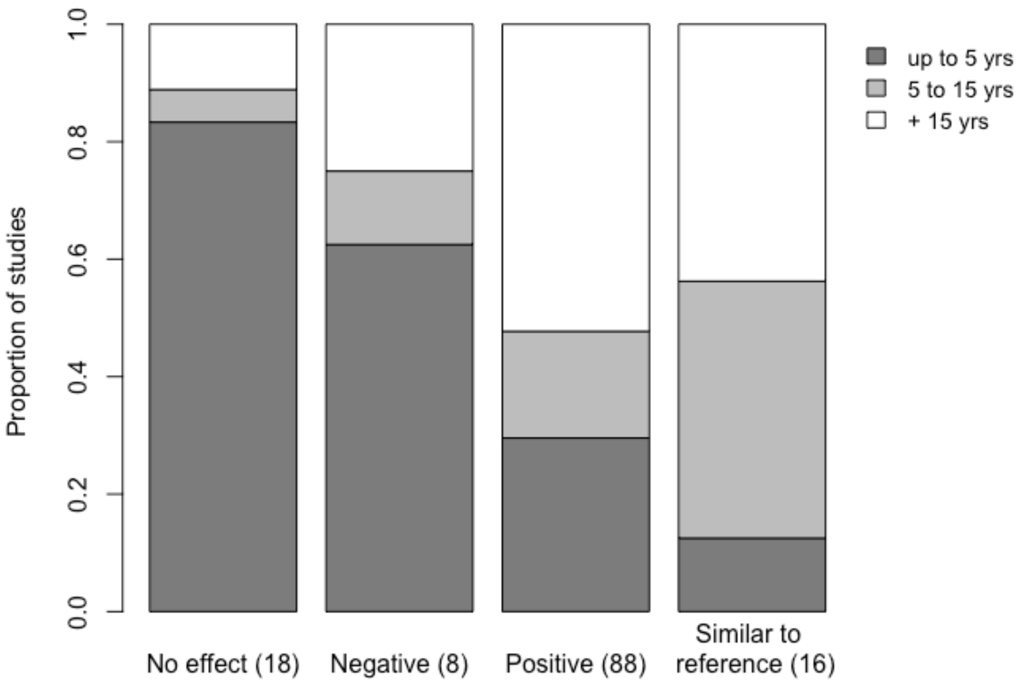

Figure 1.1. Results found in the studies included in our search (based on 153 processes). We grouped results in no effect, negative, positive or similar to reference, separating by restoration age (up to 5 years – darkgrey, 5 to 15 years – lightgrey, and more than 15 years – white). Numbers next to results represent the number of studies considered in each category. See text for further explanation.

1.4 Discussion

Our results showed a high number of studies that evaluated different functions in forests undergoing restoration, such as nutrient cycling, ecosystem resilience, productivity and water relations. Positive results of restoration on ecological processes were more frequently found in oldest sites (more than 15 years since the start of restoration), as ecological processes may take a long time to recover (Matzek et al. 2016). This reinforces the need for long term monitoring in order to evaluate recovery trajectories and changes across different ecological processes. It also highlights the need for intermediate goals to determine restoration success, as functioning at younger sites will differ when compared to old growth, mature forests. Our search still found that only a few studies addressed important biotic interactions, such as dispersal and pollination, a gap also verified in a recent review on ecosystem functions and ecological restoration over the entire range of ecosystems (Kollmann et al. 2016).

In the paragraphs below, we highlight the importance of each function category, providing information regarding the ecological processes associated in the context of forest dynamics and list the variables that are commonly used to evaluate them, taking as reference the studies listed in our search. We also identify relationships with other ecological processes and the provision of some relevant ecosystem services.

1.4.1 Nutrient cycling

Nutrient cycling is one of the most important processes in terrestrial ecosystems. Through the transformation of organic and inorganic compounds nutrient cycling promotes nutrient availability for plant growth and determines primary productivity (Van Der Heijden et al. 2008). Soil microbes (bacteria and fungi) are responsible for positive effects on plant growth, such as nutrient acquisition through litter decomposition and nitrogen mineralization, but they can also promote negative effects, through pathogens and nutrient immobilization (Wardle et al. 2004; Van Der Heijden et al. 2008). Nutrient cycling provides the supporting service of maintaining of soil fertility and can be measured by soil formation, symbiotic nitrogen fixation and nitrogen mineralization (MA 2005; Ghaley et al. 2014).

There is a tight linkage between litter production and nutrient cycling (Guariguata and Ostertag 2001), which makes it harder to separate the individual effect of each process. Litter is a carbon source for soil decomposers and the soil biota promotes the breakage of dead material and soil nutrient availability for plants (Wardle 1999). Litter decomposition is affected by climate (abiotic conditions) and by litter quality and soil biota (Couteaux et al.

1995; Wardle et al. 2004; Zhang et al. 2008), but some studies state that soil microbes may contribute up to 100% to litter decomposition (Van Der Heijden et al. 2008). Species composition and plant diversity determine litter quality and can have strong effect on soil carbon sequestration (De Deyn et al. 2008; Lange et al. 2015) and on the diversity of decomposer communities (Chomel et al. 2016).

Most of the sampled studies measured nutrient availability (nutrient pools), which was considered an indicative of nutrient cycling. Soil nutrient availability encompasses soil mineral compounds or organic matter pools; it relates to the quantity and availability of resources in the soil and can be evaluated by analyzing samples collected from the study site. Soil biotic processes on the other hand revolve on interactions between biotic components and the resources available in the soil, encompassing variables such as decomposition, earthworm activity, fungi diversity and microbial activity (e.g. N-fixing bacteria). This last category is a better indicator of nutrient cycling, as it focuses on the interaction between biotic components and the actual transformation of organic matter and incorporation to the soil (as opposed to the simple quantification of nutrient pools). We found that, for both types of measures (nutrient availability or biotic processes), papers showing positive results increased with time since the start of the restoration project. Changes in vegetation structure and composition can potentially modify decomposition rates (Podgaiski and Rodrigues 2010) as they alter microclimatic conditions, provide new resources for the soil biota and protect ground layers (Meloni and Varanda 2015). Also restoration interventions were found to promote positive change in measures of carbon and nitrogen pools in the Atlantic Forest (Nogueira Jr. et al. 2011). Successional dynamics in forests undergoing restoration promote increasing similarity towards mature forests with regard to faunal composition (Meloni and Varanda 2015) and soil properties (Matzek et al. 2016), even though soil characteristics and soil networks may take a long time to recover (Matzek et al. 2016; Morriën et al. 2017).

1.4.2 Productivity

Forests account for 35% of global plant productivity (Clark 2004), which can be defined as the total new organic matter produced during a specific interval (Clark et al. 2001). Productivity and aboveground biomass are highly dependent on nutrient cycling (soil conditions) and abiotic conditions, such as temperature and rainfall, one of the reasons why its rates are higher in the tropics (Castilho et al. 2006; Raich et al. 2006; Saatchi et al. 2007). Through the accumulation of carbon in different plant components (trunk, roots, branches and leaves), tree growth provides very important ecosystem services, such as climate regulation and timber production (De Groot et al. 2002). It can also provide food (wild fruits and seeds), medicinal and ornamental resources, moderation of extreme events (storm protection and flood prevention), regulation of water flows (natural drainage, drought prevention) and erosion prevention (MA 2005).

Productivity can be expressed as net increments in live above- and belowground biomass or by losses of materials, such as litter fall, which represents the material that comes back to the soil in form of dead organic matter (Clark et al. 2001). The most common measure of productivity encompasses aboveground plant biomass and represents measures of biomass stocked in stem, branches and foliage. Belowground biomass can be measured by root production or root turnover, but it is a measure that is less frequently assessed. Our results showed 74% of studies focusing on measures of biomass stock (in litter, above- or belowground tree biomass), rather than biomass rates (production or loss of material, for example, litter production, litter fall or growth rates).

An important feature of productivity in forest ecosystems is that rates of production and accumulation of biomass change during forest succession (Pregitzer and Euskirchen 2004). There is higher production of biomass in early succession, but rates of biomass accumulation decrease in advanced stages (Gehring et al. 2005; Marin-Spiotta et al. 2007). In the initial stages, more biomass is allocated on resource acquisition tissues, with higher litter production and low wood stock (Guariguata and Ostertag 2001; Chave et al. 2006). As succession progresses to advanced stages, biomass (carbon) stocks peak but the rate of production is lower (Guariguata and Ostertag 2001; Gehring et al. 2005; Marin-Spiotta et al. 2007). Large trees, which represent a low proportion of total stems account for the majority of plant biomass in forest ecosystems, reaching over 50% of total tree biomass (Dewalt and Chave 2004; Gehring et al. 2005; Lutz et al. 2012). In restoration sites, productivity is supposed to increase in its early stages and biomass accumulation will increase as succession progresses, with trees becoming larger and forest structure more complex (Shimamoto et al. 2014; Matzek et al. 2016). As expected, our search found increased biomass stock in older forest sites, confirming that biomass accumulation increases as succession progresses. The majority of the measures used to assess productivity focused on biomass stock, as data collection is less complex when compared to growth rates. If measurements on biomass stock are collected at different moments in time and/or compared to reference sites, they can give important results on the assessment of site productivity.

1.4.3 Ecosystem resilience (natural regeneration)

Natural regeneration is one of the most frequent measures of ecological processes in forest restoration as it can indicate changes along succession related to increases/decreases in species diversity and seedling abundance. Recruitment of seedlings in the forest depends on many steps, such as the arrival of seeds, avoidance of predation, germination and finally seedling survival and growth (Holl et al. 2000). Many factors prevent or slow natural regeneration, including soil characteristics, vegetation structure, competition with grasses or shrubs, and predation (Holl et al. 2000; Souza and Batista 2004). Natural regeneration can be related to many ecosystem services, because it provides community sustainability through the maintenance of species populations: provisioning services such as food (fruits), raw materials (fiber, timber) and maintenance of genetic diversity (MA 2005).

In our results, natural regeneration was evaluated manly through seedling/sapling density or richness (83%), and other measures included seed bank and seed density. Changes in seedling density and richness across time can provide information of the arrival and establishment of different species in the understory. These measures however give insights into the final result of this process (e.g. abundance, richness) and do not measure directly the mechanisms that promote these results (e.g. arrival, germination). In ecological restoration natural regeneration is strongly affected by decreased seed dispersal, high predation, nutrient limitation and competition with herbs/shrubs, which slow ecosystem recovery (Holl 1999; Holl et al. 2000; Hooper et al. 2002). Recruitment of new tree species will depend on their arrival in the degraded site and also their survival when facing hard environmental conditions and increased competition and predation (Reid and Holl 2013). Seedling density and richness, however, is expected to increase with time since the start of the restoration (Bertacchi et al. 2016). It is also important to mention that planted trees will probably be replaced by species growing in the understory (Suganuma et al. 2014), therefore changing species canopy composition, highlighting the importance of natural regeneration for forest growth and ecological restoration.

1.4.4. Water relations

The dynamics related to water availability are essential to the survival and growth of plant and animal species in any ecosystem. In forests they affect soil moisture and determine the activity of the faunal community and plant growth. Soil hydrological properties can potentially recover during forest recovery to values found in reference ecosystems (Hassler et al. 2011). Our results showed that water relations were mainly assessed through measures of soil moisture (72%), but also through infiltration and surface runoff. As like other processes described above, age of restoration had a positive effect on water relations (e.g. increased moisture and decreased runoff), indicating that aboveground forest recovery provides more favorable conditions for the improvement of water dynamics. Understory vegetation growth can also reduce erosion and surface water runoff (Jacobs 2015). Measures of water relations will also be strongly influenced by the site past land use and abiotic conditions: increased soil compaction may reduce water infiltration (Suganuma and Torezan 2013), decreasing soil moisture and favoring water runoff. Water relations is an important function that provides provisioning services, such as water (for drinking and irrigation), and regulating services, such as water flows (natural drainage and drought prevention).

1.4.5 Biotic interactions

Biotic interactions include plant-plant interactions (such as facilitation), plant-animal (dispersal, pollination, herbivory or mutualism) and animal-animal (predation) interactions. The interactions between organisms in a community provide important ecosystem services, such as pollination. Pollination provides an essential ecosystem service for agricultural activities: production of many types of agricultural crops depends on natural pollinators such as birds and insects. The costs for replacing natural pollinators can reach US$ 1 billion dollars a year, but crops near native fragments have important and sometimes full contribution from wild species to pollination (Kremen and Ostfeld 2005). Even though less accounted for in our survey, when compared to the other functions, biotic relations also showed positive results of restoration with increase time since the start of the restoration: positive results were twice as high in older sites. This highlights to the importance of site age to the recovery of several ecological processes.

The most common biotic interaction in our search was pollination and measures were related to flower availability or flower visitation for pollinators (e.g. flower cover, flower visitation rate, pollen flow). These measures indicate the potential of increasing pollination and consequently fruit production. Dispersal is another key process in maintaining species diversity and increasing species richness in forest ecosystems. In our search, variables considered as dispersal were seed removal, seed dispersal (bird activity) and seed dispersal networks. These measures indicate the performance of dispersers in removing seeds across the space (Lomov et al. 2009) and also the availability of different groups of dispersers associated to a larger range of seed species (Ribeiro da Silva et al. 2015). Seed removal by ants was shown to be greater in revegetated sites when compared to pastures (Lomov et al. 2009), as increased vegetation cover promotes seed movement by ants (Dominguez-Haydar and Armbrecht 2011). Restored sites at younger and older stages did not differ in the rate of seed removal from the reference condition (Lomov et al. 2009; Dominguez-Haydar and Armbrecht 2011). Dispersal can be a very important factor limiting forest recovery (Holl 1999), because of the absence of dispersers mainly due to increasing distance from forest remnants, but few studies directly consider dispersal as a monitoring tool. In restoration sites, seed dispersal is affected by elements that attract dispersers such as existing perches, structural complexity of the vegetation and attraction by fruits (Wunderlee 1997). Time since the start of the restoration increases bird-plant interactions and results in a greater complexity of dispersal networks in older sites (Ribeiro da Silva et al. 2015). Techniques for attracting dispersers to degraded sites include the use of perches. Bird perches may increase seed dispersal but attention should be given so that seedlings can survive and grow in the degraded site, otherwise high seed dispersal will not increase seedling abundance (Reid and Holl 2013).

Mutualism (excluding pollination) and herbivory were assessed in only three studies each. Restoration had positive effects on the activity of ants using sugar resources from plants (Gibb 2012). Herbivory is usually not a desired interaction in restoration sites as it can limit the survival of established seedlings and slow vegetation recovery. Herbivory measures included protection from herbivory, which increased sapling cover and density (Sitters et al. 2012), and herbivory rates, which did not differ between restoration and reference conditions (Hernández et al. 2014). Facilitation and predation were not assessed that often, they encompassed only two and one studies respectively. Measures of facilitation included increased plant survival or growth mediated by the presence of other groups of plants (e.g. legumes or pioneer species). This interaction is especially important in sites subjected to severe environmental conditions, such as seasonal or dry forests. In cloud forests, where environmental conditions are harsh due to elevation, early successional species can play a facilitator role and promote the establishment of late successional species (Avendaño-Yáñez et al. 2014), increasing the success of restoration interventions. Finally, the measure used to evaluate predation in the only study that was included in our survey was animal foraging behavior (e.g. prey attack and predation risk). Predation can also be evaluated by testing the natural control of agricultural pests, such as aphids and dipteran pests (Porter et al. 2009).

1.5 Conclusion

Our study provides a broad description on how functions are affected by different site components in forest ecosystems, indicating the way that restoration promotes changes on the ecological processes. Based on a literature survey, it indicates the processes being monitored in forest sites undergoing restoration and the field measures used to evaluate ecosystem functioning and restoration success. Nutrient cycling was the most evaluated function and biotic interactions showed the lowest frequency among the studies, as also suggested by Kollmann et al. (2016). Many of the measures used to assess functions related to pools, such as carbon and nutrient pools, might not directly report on the process in hand unless measurements are repeated over time or compared to reference conditions. Finally, we have shown that positive results on the recovery of the ecological processes increase with time since the start of the restoration, indicating that long term monitoring is needed to determine if restoration interventions were successful. Monitoring restoration sites requires a focus on ecosystem functionality in order to evaluate ecological interactions, allowing the assessment of the delivery of ecosystem services and the goods that can be obtained from restoration.

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1.7 Supplementary material

Table S1.1 whose legend reads "**Table S1.1**. List of the 106 studies and 153 processes that met the selection criteria and were included in our search, as well as the information extracted from each study" can be found in Appendix I, in the end of this volume.

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CAPÍTULO 2

Avaliando o funcionamento do ecossistema em florestas em restauração

Assessing ecosystem functioning in forests undergoing restoration

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As citações e referências bibliográficas deste capítulo seguem as normas da revista *Restoration Ecology*. Figuras e tabelas foram inseridas no corpo do texto de modo a facilitar a leitura.

Assessing ecosystem functioning in forests undergoing restoration

Abstract

Restoration projects may have broad and complex ecological goals, which in turn require distinct and integrative measures for evaluating restoration development and success. However, most studies usually evaluate only structural and species composition parameters, with little emphasis on ecosystem processes and functioning. The main objective of this study is to use an integrated approach that considers structural and floristic parameters as well as ecological processes and functional traits to evaluate and identify the parameters that most differentiate forests undergoing restoration and their reference sites. The study was performed in three 10 year-old restoration and three adjacent reference areas located in the South of Brazil. Sampling was performed in a total of 15-100 m^2 sample units per treatment, per site. We collected data of adult trees, natural regeneration, litter stock, decomposition, detritivory and litter and soil C:N ratio. In addition we used a multifunctionality index to analyze differences and relationships with other parameters. Results showed several differences between treatments for the ecological processes, indicating that restoration has not yet achieved values similar to the reference ecosystem. Also restoration sites had lower values of vegetation structure, multifunctionality and species richness, but higher values of functional diversity. Moreover, even though values were lower for multifunctionality, differences towards reference sites were less pronounced than we expected when compared to values of vegetation structure, showing that ecological processes may recover even before the full recovery of structural complexity.

Keywords: multifunctionality; ecosystem process; functionality; functional traits; subtropical forest.

2.1 Introduction

Restoration ecology aims at the recovery of ecosystems with the goal of creating a natural ecosystem that is both functional and that provides habitat for many different organisms (SER 2004; Aronson et al. 2006). In this context, it is usually targeted to reach reference conditions, which is a preserved ecosystem that resembles the one that occurred prior to degradation (SER 2004). For years, this meant planting the same native species found in the reference sites, with the objective of creating a community more similar with regard to species composition. Although trees are an important component, forest restoration is not just about planting trees (Mayfield 2016). Different targets can be achieved in ecological restoration, from species composition and forest cover, to the recovery of ecosystem processes and provision of ecosystem services. In this sense, to reach broad and complex goals in restoration projects may require a full monitoring approach that encompasses different measures of forest recovery to achieve ecological values similar to reference conditions.

Forest restoration is usually evaluated through structural parameters and also measures of species richness/diversity, with little emphasis on the evaluation of ecosystem processes (Ruiz-Jaen & Aide 2005; Rodrigues et al. 2009; Wortley et al. 2013). Studies that do not explicitly acknowledge ecosystem processes assume that the reestablishment of species richness and vegetation structure promote the recovery of these functions (Ruiz-Jaen & Aide 2005). However, the recovery of ecological processes, such as leaf decomposition, primary productivity, natural regeneration and seed dispersal, may not happen at the same time as the recovery aboveground vegetation (Palmer et al. 1997; Matzek et al. 2016), given that the complexity needed might still not be established for these interactions to happen. These ecological processes are essential to assess ecosystem functionality and the interaction between species and the environment. More recently, studies pointed out to a growing focus on ecosystem functions and on ecological processes in restoration areas (Wortley et al. 2013; Kollmann et al. 2016), but more functions should be considered and a broader view of the biodiversity-ecosystem relations are necessary to improve the functional understanding of restored communities (Kollmann et al. 2016).

The SER/Primer (SER 2004) established a large set of parameters that should be accounted for in ecological restoration, from species assemblage to functional groups, landscape characteristics, and self-sustainability, which makes it an ideal but dificult reference to be used in restoration practice due to the high financial resources and long time frame required for monitoring (Ruiz-Jaen & Aide 2005). The search for the best indicators to determine the success of ecological restoration is broad and is always an intense debate among researchers (Reid 2015; Suganuma & Durigan 2015; Brancalion & Holl 2016). However, many studies did not measure a large set of parameters (Ruiz-Jaen & Aide 2005) that would encompass different community and ecosystem properties and that could broaden the discussion on ecosystem functionality. It is suggested however that at least a few different parameters be accounted for, that includes variables related to species composition, structural complexity, functional characteristics and also socio-economic context (Ruiz-Jaen & Aide 2005; Reid 2015; Suganuma & Durigan 2015; Suding et al. 2015; Brancalion & Holl 2016).

Ecological processes (such as biomass stock, nutrient availability, seed dispersal and pollination) influence ecosystem functionality and are essential to the self-sustainability of forest restoration. Many restoration studies show changes in ecological processes with restoration interventions: litter production and turnover enhance the incorporation of nutrients and organic matter into the soil (Ruiz-Jaén & Aide 2005); planting age positively affects litter accumulation due to tree abundance and canopy cover (Mota & Torezan 2013); seedling density and richness gradually increase from young to old restoration plantings (Bertacchi et al. 2016); and cycling of nitrogen increases with restoration age (Amazonas et al. 2011).

More recently, and due to its effect on ecosystem functioning, functional traits are being used in restoration ecology (Martínez-Garza et al. 2013; Ostertag et al. 2015; Rosenfield & Müller 2017). Since they reflect the variability in species characteristics, they could be used as a tool to evaluate specific functions of the ecosystem. Thus, once ecosystem functionality embraces various processes, multiple parameters are necessary to provide a broader evaluation of restoration success.

Studies on natural succession in secondary forests show that even 100 years of recovering stands are not equal to old-growth forests (Dent et al. 2013) and that trajectories of vegetation recovery can be very unpredictable (Norden et al. 2015). For this reason the specific targets for restoration have to be clearly defined so that monitoring can use the best set of parameters to determine the eventual success of the restoration project. When focusing on ecological restoration the reference ecosystem can be a mature or secondary forest that represents the former state of the current restoration site. Monitoring both the site undergoing restoration and the reference ecosystem enables the evaluation of successional trajectories and the desired characteristics aimed during forest recovery. Some questions emerge from this topic: how do processes vary across a larger time frame? Do different ecosystem parameters related to vegetation growth perform in the same way and at the same rate? How can different measures of ecosystem functionality (e.g. multifunctionality; Byrnes et al. 2014) contribute to the evaluation of project success? To answer these questions, long time monitoring of restoration sites is required since ecosystem recovery and the characteristics found in the reference sites may take decades to recover (Liebsch et al. 2008; Benayas et al. 2009; Suganuma & Durigan 2015).

In this study we evaluated the recovery of forest restoration sites using multiple parameters related to vegetation structure, species diversity, functional traits and ecological processes, and compared with values found in adjacent reference forests. The main objective of the study is to: (i) use an integrated approach of community and ecosystem related parameters to identify the parameters that most differentiate forests undergoing restoration and their reference sites; and (ii) evaluate the size of these differences when analyzing vegetation structure, ecosystem functionality and species/functional diversity, i.e. assess if the recovery of ecosystem parameters is similar to or faster than structural parameters. We collected data on trees, seedlings, litter, decomposition, detritivory, soil and functional traits, providing a broad evaluation of different parameters affecting ecosystem function. For objective (i), due to the early regeneration stage of the restoration sites (approximately 10 years-old), we expect variable values of vegetation structure, ecosystem functionality and species/functional diversity to be lower in restoration sites when compared to reference sites. More specifically for the ecological processes, our expectation is that when compared to the reference ecosystem, restoration sites will show: for regeneration, lower values of seedling density due to poorer microsite conditions for seedling establishment (Bertacchi et al. 2016); for decomposition, lower rates of decomposition due to higher values of decomposition found in mature forests when compared to secondary forests (Martius et al. 2004); for litter stock, higher values of litter accumulation in younger sites due to lower rates of litter decomposition (Martius et al. 2004); for detritivory, higher consumption in restoration sites due to canopy openness, since temperature affects bait-lamina feeding activity (Gongalsky et al. 2008); and for litter and soil C:N ratios, higher values of carbon when compared to nitrogen due to lower quality in younger sites, as a result of lower abundance of nitrogen-fixing species (Martius et al. 2004) and also because nitrogen cycling is expected to increase in older restoration sites (Amazonas et al. 2011). For objective (ii), we expect a slower recovery of ecological processes when compared to structural parameters due to a lower ecosystem complexity in restoration sites, which affects trophic and biotic interactions.

2.2 Material and methods

2.2.1 Study site

We conducted this study in three restoration sites with three adjacent reference areas located in the South of Brazil (Table 2.1). Restoration and reference areas were adjacent to each other in all sites. The climate ecoregion is subtropical humid forest (FAO 2012) and the climate is characterized as Cfa (Peel et al. 2007): lacking a marked dry season and with warm summers. In all sites, restoration interventions were performed using seedlings from native species and the plantation strategy was lines of planting. Information regarding the restoration projects was gathered with the companies in charge of the interventions. Additional information from study sites is provided in Table 2.1.

Table 2.1. Site information encompassing characteristics on the forest type, restoration interventions and site area for each study site.

Site	Forest type	Restoration information	Site area (ha)
Cachoeirinha 29°52’41” S 51°05’48” W Elevation: 30 m	Seasonal riparian forest inserted in a degraded urban matrix. Only a few forest remnants are found near the study site.	Age: 12 years. Land use history: cattle grazing. Restoration intervention: planting of seedlings (ca. 23 native species) performed in 2001. Lines of planting (2 x 2 m).	Reference: 2.8 Restoration: 2.4
Canela 29°22’43” S 50°43’50” W Elevation: 612 m	Seasonal forest. Inserted in a vegetated, rural matrix. Forest remnants can be found near the sampled sites.	Age: 8 years. Land use history: eucalyptus plantation. Restoration intervention: planting of seedlings (ca. 34 native species) performed in 2007, after removal of eucalyptus trees. Lines of planting (2.5 x 2.5 m).	Reference: 1.6 Restoration: 2.6
Santa Tereza 29°09’27” S 51°41’45” W Elevation: 240 m	Seasonal forest. Inserted in a vegetated, rural matrix. Forest remnants can be found near the sampled sites.	Age: 10 years. Land use history: grape cultivation. Restoration intervention: planting of seedlings (ca. 21 native species). Lines of planting (2 x 2 m).	Reference: 2.3 Restoration: 2.0

2.2.2 Sampling design

In order do examine differences between restoration and reference sites relating to vegetation structure, species composition, diversity, functional measures and ecological processes we used 15-100 m^2 sampling units per treatment (restoration vs. reference) in each study site. The main sampling unit (100 m^2) was used for the survey of adult trees (diameter at breast height – DBH $\geq$ 5cm) and the other parameters were sampled in 3 sub-plots inside each main sampling unit. Structural parameters from adult trees used in this study were: total basal area, stem density and mean height. See Table 2.2 for further details on data sampling.

We used functional trait measures from leaf, reproductive and growth traits to evaluate functional differences between treatments. These functional traits are part of the plant economics spectrum, influencing growth rates, dispersal strategies, resource use efficiency, and affecting successional trajectories and ecosystem processes. We used trait information from a database from the Plant Ecology Lab at the Universidade Federal do Rio Grande do Sul (LEVEG/UFRGS, Brazil), which follows the protocol proposed by Perez-Harguindeguy *et al.* (2013; except for reproductive traits which are based on a literature compilation). This database results from a regional effort of sample collection and includes most of the tree species found in the state of Rio Grande do Sul, Brazil. In cases where species included in our forest survey were not fully covered in the database (less than 5 individuals per species), we also collected leaf samples in the field. Traits included in this study were: leaf traits – leaf area (LA, mm^2), specific leaf area (SLA, mm^2 mg^{-1}), leaf dry mass content (LDMC, mg g^{-1}), leaf nitrogen and phosphorus content (LNC and LPC, proportion of total mass); reproductive traits – seed mass (SM, g) and mean fruit size (FS, cm^2); and also growth traits – maximum height (MH, m) and wood density (WD, g cm^{-3}).

Table 2.2. Full description of the parameters included in the study and detailed information on data collection.

Parameters measured	**Sampling**	**Database**
VEGETATION STRUCTURE		
Basal area Mean height Stem density	Sampling units of 100 m^2 (SU); 15 SU per treatment, per site	We included all adult trees with DBH $\geq$ 5 cm (DBH: diameter at breast height), measured the DBH (cm) and mean height (m) for all trees. Values represent: total stem area per SU for basal area (m^2), mean height per SU, and total stem count per SU for stem density.
DIVERSITY AND FUNCTIONAL MEASURES		
Diversity measures		
Species richness Inverse Simpson	Sampling units of 100 m^2 (SU); 15 SU per treatment, per site	From the vegetation structure survey we identified all trees to species level whenever possible and calculated the total number of species per SU (species richness) and the Inverse Simpson diversity measure.
Functional measures		
Functional diversity (Rao's quadratic entropy) Community weighted trait means (CWM)	*Leaf traits*: Mean values of 5 individuals per species; values of each individual are based on 10 leaves. *Reproductive and growth traits*: Data from literature compilation	We used leaf, reproductive and growth traits. *Leaf traits*: LA (leaf area, mm^2), SLA (specific leaf area, mm^2 mg^{-1}), LDMC (leaf dry matter content, mg g^{-1}), LNC (leaf nitrogen content, proportion of total mass) and LPC (leaf phosphorus content, proportion of total mass); *Reproductive traits*: seed mass (SM, g) and fruit size (FS, cm^2); *Growth traits*: maximum height (MH, m) and wood density (WD, g cm^{-3}). We calculated the community weighted mean value for each trait using tree species abundances per SU. Rao's quadratic entropy was also calculated using tree species abundances per SU, considering all nine functional traits (leaf, reproductive and growth traits). Data was extracted from the functional traits database from the Plant Ecology Lab at the Universidade Federal do Rio Grande do Sul (LEVEG/UFRGS), which follow the protocol proposed by Perez-Harguindeguy et al. (2013).
ECOLOGICAL PROCESSES		
Regeneration (seedling and sapling density)	3 sub-plots of 4 m^2 (2 x 2 m) per SU	We sampled all tree seedlings and saplings with height greater than 30 cm and DBH $<$ 5 cm. We summed the values of each sub-plot (12 m^2) and then extrapolated to the main SU (100 m^2).
Litter stock	3 sub-plots of 0.25 m^2 (0.5 x 0.5 m plot) per SU	We collected all leaves above the soil surface within the limits of the sub-plot. The material collected in the field was subject to triage in order to remove any branches, reproductive material and sand that might eventually had been collected. We then dried the leaf litter material at 70ºC for at least 72 h and measured its final dry weight. Values of litter stock (kg) for the 3 sub-plots were summed and then extrapolated to the 100m^2-SU. We performed two field campaigns: in autumn (March to June) and spring

Parameters measured	**Sampling**	**Database**
		(September to December). Final litter stock was considered the mean value of both campaigns.
Decomposition	3 sub-plots of 0.25 m^2 (0.5 x 0.5 m plot) per SU; 1 litterbag per sub-plot	We evaluated decomposition using litterbags (plastic net of 2 mm mesh size) filled with standard material (5 g of cellulose paper). Litterbags were installed directly in the soil surface, removing all leaf litter beforehand. We placed 1 litterbag per sub-plot and they stayed in the field from 17 to 20 weeks. In the laboratory, the remaining material was cleaned (from leaves and soil), dried for 72 h at 65ºC and finally weighted. The remaining material was subtracted from the initial weight (5 g) to obtain the proportion of paper decomposed during the period. Although time exposure in the field was not the same across sites (due to logistical purposes), we managed to remove litterbags in each site from both treatments at the same time, assuring the comparison between treatments.
Detritivory	3 sub-plots of 0.25 m^2 (0.5 x 0.5 m plot) per SU; each sub-plot contained 3 bait-laminas	We evaluated detritivory using the bait-lamina test. All holes from the wood stick were filled with a mixture of flour, cellulose and distilled water. Laminas were placed horizontally in the soil surface layer and remained in the field from 14 to 18 days. We then took the sticks to the lab, air dried for 24 hours and counted the empty holes using a magnifying glass. Consumption was considered only if the hole was empty (no bait) and the parameter used in the analysis was the proportion of empty holes per stick. Values of detritivory were considered the mean consumption per SU. We performed two field campaigns: in autumn (March to June) and spring (September to December). Final detritivory consumption was considered the mean value of both campaigns. Although time exposure in the field was not the same across sites (due to logistical purposes), we managed to remove bait-laminas in each site from both treatments at the same time, assuring the comparison between treatments.
Litter and soil C:N ratio	1 composed sample made of 3 sub-samples per SU	We performed carbon (C) and nitrogen (N) analysis on both litter and soil. For each SU we used a composed sample of three sub-samples. *Litter*: we mixed the three sub-samples collected for the litter stock measurements (described above). *Soil*: we collected and then mixed together three small samples (10 x 10 cm) from 0-10 cm deep in the soil surface. The chemical methods used were: humid combustion, Walkey Black/0.01% for organic carbon and Kjeldahl/0.01% for nitrogen (TKN). Chemical analysis were performed in the Laboratório de Solos of the Universidade Federal do Rio Grande do Sul. We used in our analysis the C:N ratio for both litter and soil.
Multifunctionality	-	We calculated a multifunctionality index for each SU, based on the multiplication of all parameters related to the ecological processes: seedling density, litter stock, decomposition, detritivory, litter C:N ratio and soil C:N ratio.

Parameters measured	Sampling	Database
		Data was first reflected (if necessary) and then standardized (divided by the maximum value) prior to calculation. See main text for further details.

To account for species diversity and functional composition of canopy trees, we calculated for each plot: species richness (we rarified species richness to remove the effect of differences in tree density among plots), Inverse Simpson index, the community weighted mean (CWM) value for each trait and Rao's quadratic entropy (considering all nine functional traits). Tree species composition for canopy and understory species and functional composition (considering all traits) were also compared between treatments.

We collected data on local ecological processes related to regeneration (seedling density), productivity (litter stock) and nutrient cycling (decomposition, detritivory and litter and soil quality) (see details in Table 2.2). Regeneration was evaluated as the total number of tree seedlings and saplings per 100 m^2-plot (seedling density). Litter stock was considered the total amount of oven-dried dead leaves above the soil (kg/100m^2; Scoriza et al. 2012). Decomposition was estimated as the total percentage of weight loss of cellulose paper inside litterbags during a time period of 4-5 months (Olson 1963). Detritivory was calculated using the bait-lamina test (Kratz 1998) and was considered as the percentage of bait consumption during a 15-days exposition in the field. Finally, litter and soil quality were assessed through analysis of carbon and nitrogen content. We collected composed litter and soil samples and performed chemical analysis for both C and N. The variable used in this analysis was litter and soil C:N ratio. All the above parameters were measured in three sub-plots inside the main sampling unit and then extrapolated to 100 m^2 when necessary. Since we expect seasonality changes for litter stock and detritivory measures, we performed two field campaigns: one in autumn (March to June) and the second in spring (September to December). For these parameters we used the mean value in our analysis.

Apart from the use of individual parameters to analyze differences between treatments we also used a multifunctionality index to summarize all ecological processes (Maestre et al. 2012). This index accounts for the multifunctionality of the ecosystem, i.e. the ability of the ecosystem to maintain multiple ecosystem functions simultaneously (Zavaleta et al. 2010). It consists on the average value of multiple functions, in our case, the main value of all parameters related to the ecological processes (regeneration, decomposition, detritivory, litter C:N ratio and soil C:N ratio) that reflect ecosystem functionality. For the calculation, measures are first reflected (if necessary) and then standardized by their maximum value to reach the same scale (Maestre et al. 2012; Byrnes et al. 2014). Reflection is used in cases where lower values of a given parameter represent a higher level of a specific function. We reflected values for litter stock, detritivory and litter and soil C:N ratios.

2.2.3 Statistical analysis

We tested for differences between treatments (objective *i*) for all the parameters evaluated using nested ANOVA to control for differences between sites. All parameters that did not present a normal distribution were log- (basal area, mean height, tree density, litter stock, decomposition, litter C:N ratio) or square-root- (species richness and regeneration) transformed in order to reach necessary statistical requirements. We also tested differences in species and functional composition between treatments using MANOVA and plotted using non-metric multidimensional scaling (NMDS). We evaluated the size of the differences between treatments (objective *ii*) for each parameter using response ratios (the ratio between restoration/reference values) and tested equality to zero using Wilcoxon rank test. All analysis was performed with R (R Core Team 2016). Species diversity and composition measures were calculated using the *vegan* package, CWM and functional measures with the *FD* package.

2.3 Results

Species composition differed between areas undergoing restoration and reference forests within each site (Fig S2.1). For structural parameters, basal area and tree height differed between treatments, being lower in restoration sites when compared to reference forests ($p<0.001$; Table 2.3). Values for stem density however were not statistically significant between treatments ($p=0.74$). Species richness was lower in restoration ($p<0.05$; Table 2.3). Exotic species were found in all three sites, but the abundance was not high: in Cachoeirinha we found 1 species (only 1 tree), in Canela 5 species (7% of total stem density) and in Santa Tereza also 5 species (3% of total stem density; data not shown), which occurred mostly in restoration sites.

Values of CWM for functional traits showed high variability across sites and treatments (Fig. S2.2), but differences in functional composition were statistically significant between treatments according to the MANOVA in all sites ($p<0.001$). The most consistent trait was LDMC, which was lower in restoration sites across all study areas. MH and WD showed lower values in restoration, except for Cachoeirinha, and LPC was higher in restoration sites, except for Canela ($p>0.05$).

For the ecological processes, we found treatments to be statistically different from each other for all parameters evaluated (Table 2.3 and Fig. S2.3). Seedling density and decomposition were higher in the reference forest ($p<0.001$), while for the remaining parameters values were higher in restoration sites (Table 2.3).

Table 2.3. Mean (± SD) values for each parameter evaluated. All values represent measures per sampling unit (100 m^2). Symbols indicate significant differences between treatments ($p<0.001^{***}$; $p<0.01^{**}$; $p<0.05^{*}$; and non significant^{NS}) using nested ANOVA to control for differences between study sites.

	Basal area (m^2)	**Tree mean height (m)**	**Tree density (stems)**	**Species richness (#)**	**Seedling density (#)**	**Litter stock (kg)**	**Decomposition (%)**	**Detritivory (%)**	**C:N litter**	**C:N soil**
Cachoeirinha										
Forest	0.38 ± 0.16	6.6 ± 0.6	23 ± 11	3.9 ± 1.2	385 ± 150	87.1 ± 29.4	0.42 ± 0.19	0.51 ± 0.17	23.19 ± 1.81	9.84 ± 1.28
Restoration	0.16 ± 0.07	4.9 ± 0.8	12 ± 4	3.5 ± 1.1	329 ± 166	177.0 ± 76.3	0.39 ± 0.14	0.58 ± 0.20	28.94 ± 8.14	9.67 ± 0.67
Canela										
Forest	0.41 ± 0.22	8.2 ± 1.0	19 ± 6	6.4 ± 1.5	294 ± 98	70.4 ± 15.1	0.88 ± 0.37	0.60 ± 0.15	18.45 ± 0.99	7.68 ± 1.74
Restoration	0.22 ± 0.09	6.6 ± 0.8	28 ± 9	7.2 ± 1.2	341 ± 135	70.8 ± 27.6	0.59 ± 0.24	0.73 ± 0.09	26.7 ± 6.05	8.66 ± 0.60
Santa Tereza										
Forest	0.33 ± 0.18	11.0 ± 1.5	14 ± 3	5.7 ± 0.7	503 ± 160	65.6 ± 22.5	0.94 ± 0.32	0.37 ± 0.17	17.70 ± 3.11	8.03 ± 0.49
Restoration	0.15 ± 0.04	4.7 ± 0.6	17 ± 5	3.3 ± 1.5	142 ± 88	73.4 ± 23.4	0.44 ± 0.25	0.76 ± 0.19	21.66 ± 2.82	8.84 ± 0.63
Significance	***	***	**NS**	*	***	**	***	***	***	**

When ecological processes were considered in the multifunctionality index then differences were clear between restoration and forest, being lower in restoration sites (Fig. 2.1). As expected, response ratios for both structure and multifunctionality were negative (lower values in the restoration site) and statistically different from zero ($p<0.05$). The size of the differences between treatments was lower for multifunctionality than for structure, contrary to our initial hypothesis. For species richness, response ratios were also negative (lower richness in restoration) and statistically different from zero ($p<0.05$), except from one study site (Canela) where values of species richness were greater in the restoration site. A different pattern was found for functional diversity where values were greater in restoration sites ($p<0.05$) but were not statistically different for Santa Tereza ($p=0.44$).

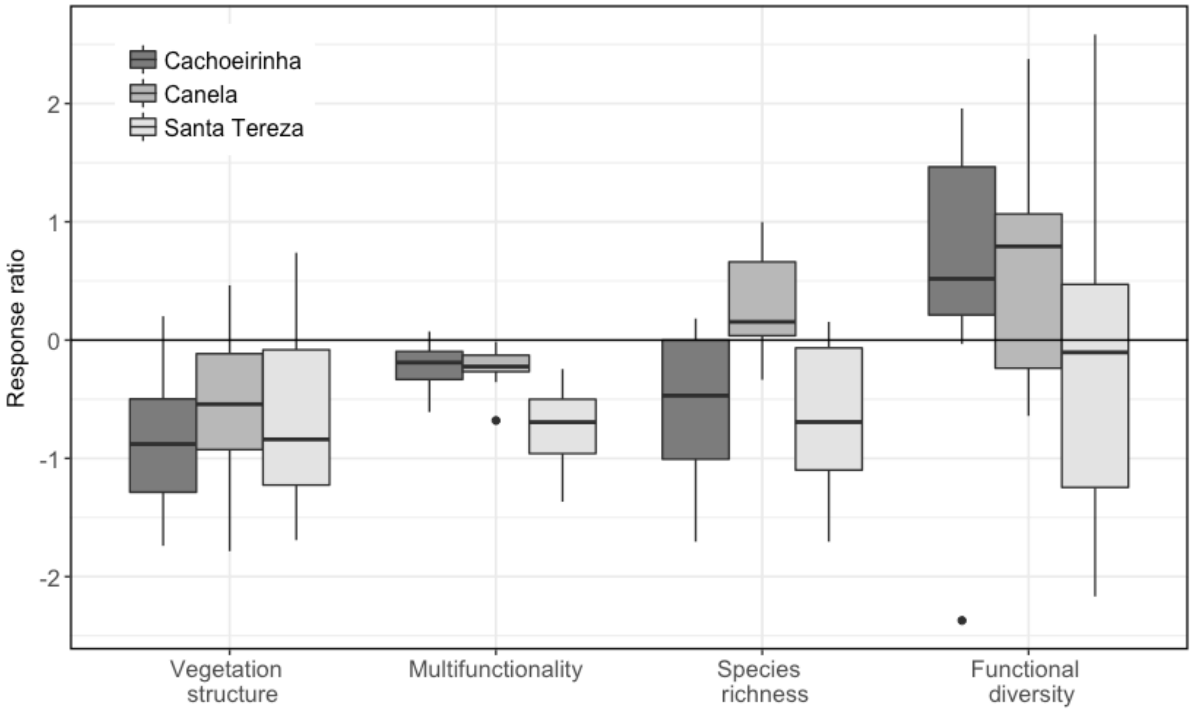

Figure 2.1. Values of response ratios (Restoration/Reference) for: vegetation structure (basal area), multifunctionality, tree species richness and functional diversity (Rao). Shades of grey represent each study site (Cachoeirinha, Canela and Santa Tereza). Values for all parameters were statistically different from zero ($p<0.05$) except for functional diversity in Santa Tereza ($p=0.44$).

2.4 Discussion

We provide a broad evaluation of 8 to 12-year-old forests undergoing restoration and their reference sites, encompassing variables related to forest structure, species richness/composition, ecological processes and functional traits. This integrative approach provides a way to assess ecosystem functionality in restoration sites and the similarity towards reference conditions. The patterns for all parameters evaluated in our study showed a considerable amount of variability across sites, but apart from a few particularities, restoration and reference sites differed for all parameters. Our initial hypothesis that structural components would recover before the reestablishment of ecological functions was not supported by our results. The size of the differences between reference and restoration were smaller for multifunctionality than for vegetation structure, which suggests that ecological processes may recover earlier than the full complexity of aboveground vegetation.

We found differences in structural parameters (basal area and mean height) between treatments, indicating a more complex structure in reference sites due to the higher values of tree basal area and mean height. This indicates that restoration sites are still far from their adjacent reference forest when we account for vegetation structure. This is a common characteristic found in many restoration studies and is directly influenced by site age: forests growing for a longer period will naturally have an advantage in incorporating their resources for growth, increasing values of basal area and tree height along succession (Chazdon et al. 2010; Zanini et al. 2014). Woody plant density on the other hand is expected to decrease with site age (Gehring et al. 2005) as increased competition mostly between young individuals causes increased tree mortality. Studies suggest that it might take from 26 to up to 50 years to recover values of vegetation structure (basal area and tree height) similar to reference, old-growth conditions (Zanini et al. 2014; Suganuma & Durigan 2015). Variables related to vegetation structure such as basal area and tree height are associated with forest structural complexity, which increases along succession and promotes changes in site conditions, such as soil properties, light availability, air temperature and moisture. These changes provide different set of resources to other organisms, facilitating the colonization of lianas, epiphytes and different animal species (Ruiz-Jaén & Aide 2005).

Results on total number of species were lower in restoration sites. For the site Canela species richness was higher in restoration possibly due to the selection of many different species for planting. Even though results of species richness show higher values in reference sites, functional diversity values did not follow the same pattern. Values of functional diversity were greater in restoration (in two sites) or non-significant between treatments (in one site). This might be related to the selection of species for planting, which in many times tends to favor species that are more different from one another (increasing trait diversity). When evaluating functional community trait means, the analysis of individual traits did not suggest strong differences between treatments across all sites (Fig. S2.2), but when functional composition was analyzed considering all traits together then differences between forest and restoration sites were significant. Similarity towards mature forests for species composition or ecosystem processes is expected to increase along succession (Dent et al. 2013; Matzek et al. 2016) and functional composition in secondary forests can even converge to values found in old-growth forests (Dent et al. 2013).

For the ecological processes, even if the pattern was not similar across all sites, we found many differences between treatments. As expected, decomposition was higher in reference forests and litter and soil C:N ratios were higher in restoration sites, indicating lower quality of plant and soil material (Martius et al. 2004). We found no difference in litter stock between treatments in two of our study sites. Due to the differences found for decomposition rates, the lack of differences in litter stock could be due to low litter input (litter fall), which would reduce the amount of material that reaches the soil surface (not evaluated in our study). Even with the high litter production in mature forests, litter stocks can be lower when compared to secondary forests, as higher decomposition prevents litter from accumulating in the forest floor (Martius et al. 2004). Our results show that forests undergoing restoration show the same pattern of early-successional stands, having lower decomposition, and higher values of C:N ratio in both litter and soil. For detritivory, bait-lamina consumption was higher in restoration sites. Although feeding activity may be lower in very degraded sites, such as mining areas (André et al. 2009), soil biota activity is affected by temperature (Gongalsky et al. 2008), which can increase bait-lamina consumption. Since canopy structural complexity (basal area and mean height) is lower in restoration sites, this can change microsite conditions and influence soil biota activity. Also, we found no relation between detritivory and litter C:N ratio or decomposition (results not shown).

We found no differences in seedling density in two of our three study sites, however species composition in the understory was different between treatments across all sites ($p<0.001$). Seedling density and species richness in the understory increase with restoration age (Bertacchi et al. 2016), as well as similarity of seedling composition along succession (Norden et al. 2009). This suggests that similarity with the reference ecosystem is still not yet achieved. Additionally, local site characteristics might explain the different trends found for seedling density and litter stock in some of our sites: the very low seedling density in Santa Tereza's restoration site may be due to soil compaction and higher temperatures found in the understory (not considered in our study), which could reduce seedling establishment; and the very high litter stock in Cachoeirinha's restoration site could be related to the presence of a very abundant species in the sampling units: *Psidium cattleyanum* (Myrtaceae). This species has large and though leaves (LA=19.07 mm^2; SLA=5.21 mm^2 mg^{-1}; LDMC=375.73 mg g^{-1}), which could slow decomposition and increase litter stock.

Our study showed that even if structural characteristics are distant from the reference ecosystem, functionality of restored sites (expressed by the multifunctionality index) seems to be performing well. Our expectation, that differences in ecological processes would be more pronounced (due to decreased vegetation complexity in restoration sites slowing the recovery of functions), was not supported by our results. We expected that forests undergoing restoration would present a less adapted trophic network that would not be performing as expected when compared to the reference ecosystem. Our results showed some different responses depending on study site, probably due to local particularities in microsite conditions, such as temperature and soil humidity, and past land use. Although these differences are important in driving the responses of forest growth, our results give a broad scenario of forest recovery in early-growth restoration sites, moving beyond the simple evaluation of forest structure and plant community composition. It is important to note that our restoration sites are young and early successional and they show potential of change in the near future, especially by the results found in Canela, given the values of vegetation structure, multifunctionality, species richness and functional diversity. Long time monitoring is necessary so that forest development is assured and management actions be taken if necessary.

2.5 Acknowledgements

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2.6 Supplementary material

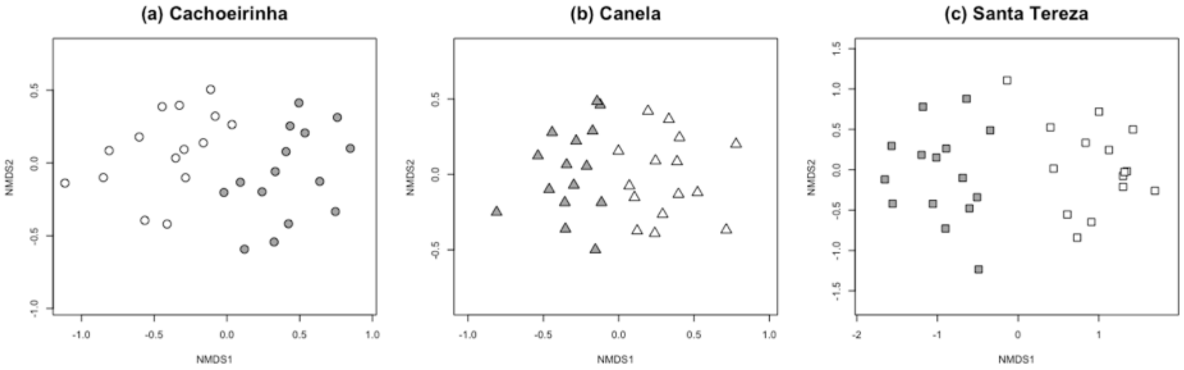

Figure S2.1. NMDS for canopy species composition in each study site: (a) Cachoeirinha, (b) Canela and (c) Santa Tereza. Colors denote forest (grey) and restoration (white). Differences in species composition between treatments were statistically significant in all sites ($p<0.001$).

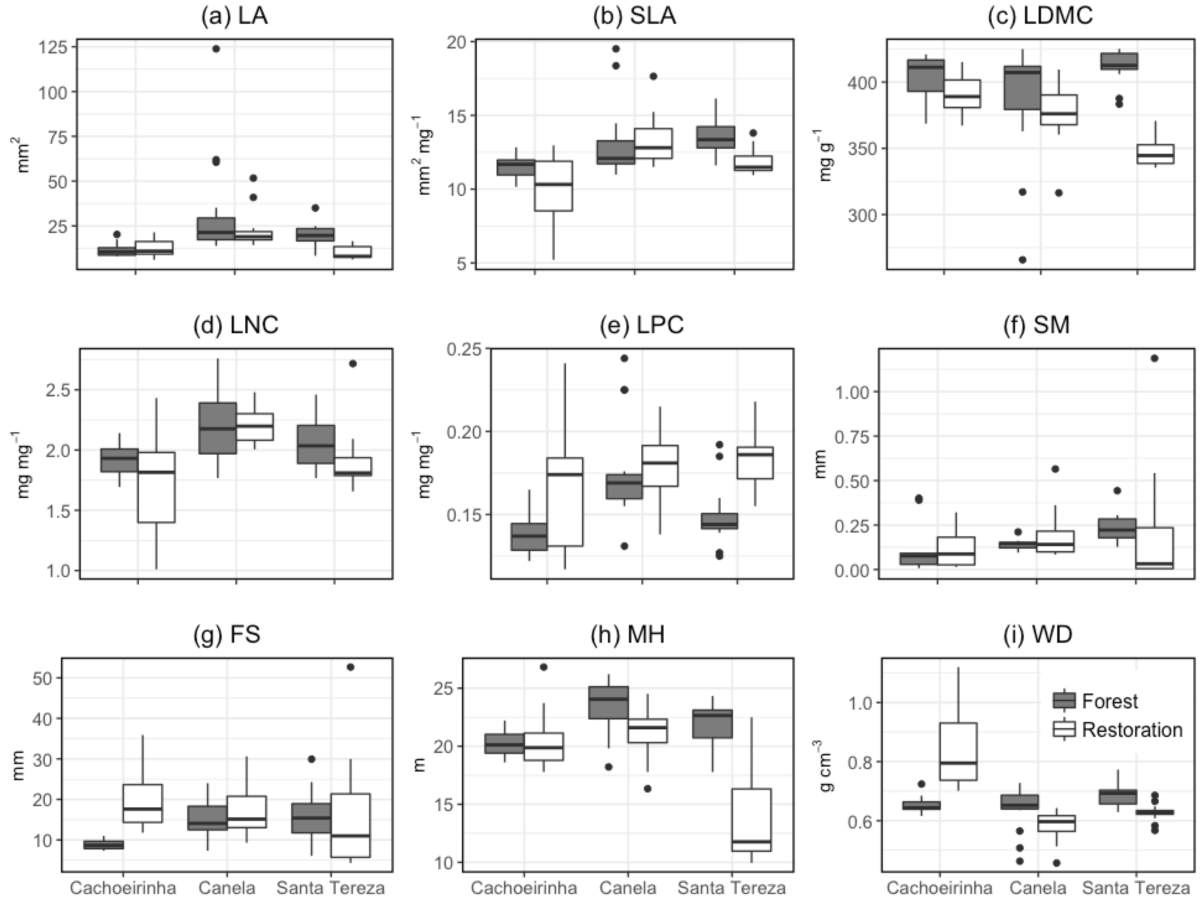

Figure S2.2. Box-plot showing the variability of all functional traits evaluated in the study: leaf area (LA), specific leaf area (SLA), leaf dry matter content (LDMC), leaf nitrogen content (LNC), leaf phosphorus content (LPC), seed mass (SM), fruit size (FS), maximum height (H) and wood density (WD). Results are grouped per site: Cachoeirinha, Canela and Santa Tereza. Treatments are denoted in grey (Forest) and white (Restoration).

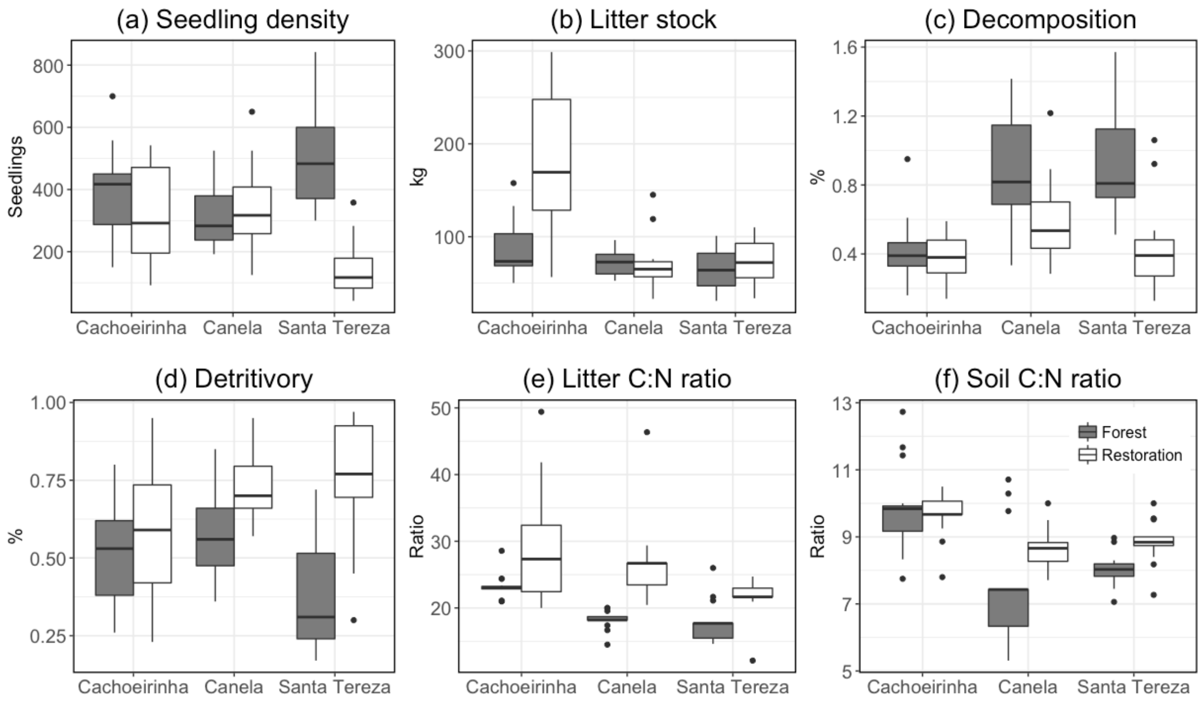

Figure S2.3. Box-plot showing the variability of all ecological processes evaluated in the study: seedling and sapling density, litter stock, decomposition, detritivory, litter C:N ratio and soil C:N ratio. Results are grouped per site: Cachoeirinha, Canela and Santa Tereza. Treatments are denoted in grey (Forest) and white (Restoration).

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CAPÍTULO 3

Efeito da riqueza de espécies e de atributos funcionais de plantas nos processos ecológicos em ecossistemas florestais

Effect of species richness and plant functional traits on ecological processes in forest ecosystems

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As citações e referências bibliográficas deste capítulo seguem as normas da revista *Functional Ecology*. Figuras e tabelas foram inseridas no corpo do texto de modo a facilitar a leitura.

Effect of species richness and plant functional traits on ecological processes in forest ecosystems

Abstract

Functional traits and species richness have been used to assess variation in ecological functions in multiple ecosystems. The effects of these different measures of biodiversity on ecosystem processes are not always clear and may show contrasting results. The correct assessment of these variables is important to evaluate the recovery of ecosystem functioning. The objective of this study was to analyze the effect of species richness and functional composition on ecological processes related to nutrient cycling, productivity and recruitment in forest ecosystems. The study was performed in three forest sites located in the South of Brazil. We collected data on understory tree abundance, aboveground tree biomass, litter stock, decomposition, detritivory, litter and soil C:N ratio. We also calculated species richness and both community-weighted mean (CWM) values and functional diversity (FD), based on species abundances in each plot, for leaf and growth traits. We found a stronger effect of CWM values on processes related to productivity and recruitment and of FD measures on processes related to nutrient cycling. Species richness showed a secondary effect on understory abundance and tree biomass, but only in association with CWM measures. Our results support both mass-ratio and niche complementary effects depending on the ecological process in hand, suggesting that both dominant species and species variability affect ecosystem functioning. They also support the stronger influence of functional trait composition rather than species number on ecosystem functionality. Our study provides evidence for the use of functional traits to assess changes in ecological processes and also to monitor forests undergoing restoration.

Keywords: biodiversity ecosystem functioning; CWM; functional diversity; functionality; subtropical forest.

3.1 Introduction

Functional traits have been increasingly used as good predictors of the effect of biodiversity on ecosystem processes and ecological functions in multiple ecosystems. The effects of biodiversity on ecosystem functions (BEF research) have been a focus of ecological studies, addressing the way through which species richness or diversity affect functions (Loreau *et al.* 2001). Plant species richness has been shown to increase biomass accumulation (Reich *et al.* 2001; Cardinale *et al.* 2007) and biodiversity to be positively related to the provision of multiple ecosystem services (Balvanera *et al.* 2006). Biodiversity is thought to provide better resource use efficiency through niche complementary effects (Naeem 2002). But the relations of biodiversity and many ecological processes are not always clear since biodiversity effects on ecosystem processes may be due to species characteristics rather than number of species per se (Díaz *et al.* 2006).

The *Millenium Ecosystem Assessment* (MA 2005) stated that the influence of biodiversity on ecosystem processes and services occurs through the effect of functional traits. This has been reported in several other studies, which stated that species characteristics affected ecosystem properties (Hooper *et al.* 2005): high leaf nitrogen content (LNC), high specific leaf area (SLA) and low leaf dry matter content (LDMC) positively affect litter quality and increase litter decomposition (Garnier *et al.* 2004; Freschet, Aerts & Cornelissen 2012); SLA positively affects aboveground biomass increments (Finegan *et al.* 2015); wood density (WD) is a good predictor of tree growth (Poorter *et al.* 2008); and seed mass increases seedling survival (Moles & Westoby 2004).

Species functional traits are measured in the organism's level and affect individual or species fitness via effects on growth, reproduction and survival (Violle *et al.* 2007). In the community level, plant species functional traits can affect ecosystem properties (Lavorel 2013). The scaling up to the community-level traits can be performed by different measures of trait composition and diversity, which provide distinct insights into their effects on ecosystem processes. Two measures are widely used in trait-based ecology: the community weighted mean trait (CWM, (Garnier *et al.* 2004)), which is a measure of trait dominance and is known to reflect the abundance of the dominant species (Ricotta & Moretti 2011); and functional diversity (FD), which is a measure of trait variability and accounts for the presence of rare species. These measures of functional composition and diversity reflect different ecological responses. Values of CWM are related to mass-ratio theory (Grime 1998), which states that the traits from the most frequent and dominant species are the ones that most affect ecological processes and ecosystem services (Díaz *et al.* 2007). Functional diversity on the other hand reflects niche complementary effects (de Bello *et al.* 2010), which refers to a more complete use of available resources by ecologically different species. Although set in theory, strong evidence is needed to separate the effect of using both measures in evaluating changes in ecosystem properties (de Bello *et al.* 2010).

In areas undergoing restoration several characteristics related to vegetation structure, floristic and functional diversity might be impaired, which can harm ecological dynamics and the provision of ecosystem services. In this context, restoration interventions should focus on the recovery of ecosystem functions (Wortley, Hero & Howes 2013; Kollmann *et al.* 2016), resembling the characteristics found in the reference ecosystem, which is the main target of restoration: a mature ecosystem that resembles the condition found prior to degradation (SER 2004). In order to increase similarity of functional composition towards reference conditions, management actions could focus on changing species abundances (and thus plant trait composition), which would thus change the set of resources available to other organisms (see Chapter 4). Thus knowing which plant traits most affect a specific function of interest could enable a better choice of management actions in order to improve functions. Although initial species composition in areas undergoing restoration is selected by humans and does not necessarily resemble the composition found in mature forests, as succession advances similarity towards mature forests increase (Dent, Dewalt & Denslow 2013). Therefore forests undergoing restoration could be understood as the initial stages of forest succession.

Here we present a field-based study in subtropical forests addressing the effect of tree species richness and plant functional traits on multiple ecological processes related to productivity, nutrient cycling and natural regeneration in forest ecosystems. We explored (i) the effect of tree species richness and plant functional traits on these ecological processes; and (ii) the influence of trait composition and structure (CWM vs. FD measures) on the processes, discussing the results in light of the mass-ratio and niche complementarity theory. We collected data on forests in advanced stage of succession and also in 10 year-old restored forests, and consider these recovering sites as the initial stages of forest succession, gathering a greater range of variability in forest structure and characteristics. Our main expectations are that: (I) species functional traits, and not number of species per se, will directly affect and predict ecosystem functioning (Díaz *et al.* 2006); and (II) CWM measures, and not FD, will most affect ecosystem processes, based on the mass-ratio theory (Grime 1998).

3.2 Material and methods

3.2.1 Study site and sampling design

We collected data on three study sites in the South of Brazil (Cachoeirinha – 29°52’41”S, 51°05’48”W; Canela – 29°22’43”S, 50°43’50”W; Santa Tereza – 29°09’27”S, 51°41’45”W). The climate from the region is characterized as Cfa (Peel, Finlayson &

McMahon 2007), lacking a marked dry season and presenting hot summers, with temperatures above 22ºC. Forest type is considered subtropical humid forest (FAO 2012), more specifically, forests are classified as seasonal semi-deciduous forests, as part of the Atlantic Forest biome (Oliveira-Filho *et al.* 2015). In each location we performed the survey in both reference forests (medium to advanced stages of regeneration) and forests undergoing restoration, which were located adjacent to each other. Both treatments in each site were located adjacent to each other and were subjected to the same temperature and precipitation throughout the year. In all sites, restoration interventions were performed using seedlings from native species and the plantation strategy was lines of planting. In this study, we do not focus on differences between reference forests and areas undergoing restoration, but consider these former degraded sites as a lower end of forest variability, showing decreased structural complexity, species diversity and functionality when compared to its reference forest (see Chapter 2 for further information).

We collected data on ecological processes related to regeneration (seedling/saplings density), productivity (aboveground tree biomass – AGB and litter stock), and nutrient cycling (decomposition, detritivory and litter and soil quality). Sampling was performed within 30-100 m^2 sampling units in each study site, encompassing 15 in reference forests and 15 in restoration. Regeneration was considered the total number of tree seedlings and saplings (height $\geq$ 30 cm and DBH $<$ 5 cm) per 100 m^2-plot (hereafter referred to as understory). We conducted an inventory survey on all adult trees (diameter at breast height – DBH $\geq$ 5cm) in order to estimate AGB. Aboveground biomass was estimated using the allometric equation proposed by (Burger & Delitti 2008), which includes DBH and height in the calculation and is expressed in kg (kg per 100m^2). Litter stock was considered the total amount of oven-dried dead leaves above the soil (kg per 100m^2; Scoriza et al. 2012), collected in 3 sub-plots (0.5 x 0.5 m) inside the main sampling unit (the samples werer summed and then extrapolated to 100 m^2). Decomposition was estimated using litterbags containing standard material (cellulose paper), installed in the soil surface, and was considered the total percentage of weight loss during a time period of 17 to 20 weeks (Olson 1963). We used 3 litterbags per sampling unit (100 m^2) and used the average value of the three samples. Detritivory was calculated using the bait-lamina test (Kratz 1998) and was considered as the average bait consumption percentage per 100 m^2. We sampled 3 sub-plots, installing 3 bait-laminas per sub-plot, which were exposed in the field for a period of 14 to 18 days. Finally, litter and soil quality were assessed through analysis of carbon (C) and nitrogen (N) content. We prepared a composed sample of litter and soil, made of 3 sub-samples collected in the 100 m^2 sampling unit, and performed chemical analysis for both carbon and nitrogen content. The variable used in this study was litter and soil C:N ratio (hereafter $\text{Litter}_{\text{CN}}$ and Soil_{CN}). See Chapter 2 for a full description of data collection for the parameters included in the study.

We used tree species richness ($\text{Richness}_{\text{spp}}$) and functional trait parameters derived from measures of leaf and growth traits to evaluate their effect on ecological processes. We calculated total number of tree species per plot (100m^2) to assess $\text{Richness}_{\text{spp}}$. We used trait information from a database from the Plant Ecology Lab at the Universidade Federal do Rio Grande do Sul (LEVEG/UFRGS, Brazil). This database is a regional compilation and includes most of the tree species found in the state of Rio Grande do Sul, Brazil, and follows the protocol proposed by Perez-Harguindeguy *et al.* (2013). Leaf traits are based from field collections and growth traits from a literature compilation. In cases where species included in our forest survey were not fully covered in the database (less than 5 individuals per species), we also collected traits in the field. Traits included in this study were: leaf traits – leaf area (LA, mm^2), specific leaf area (SLA, mm^2 mg^{-1}), leaf dry mass content (LDMC, mg g^{-1}), leaf nitrogen and phosphorus content (LNC and LPC, proportion of total mass); and growth traits

– maximum height (MH, m) and wood density (WD, g cm^{-3}). In order to evaluate functional trait composition, we calculated for each plot: the community weighted mean value (CWM) of traits and the Rao's quadratic entropy, a commonly used measure of FD (Ricotta & Moretti 2011). We calculated FD for both groups of traits: leaf (FD_{leaf}, which included LA, SLA, LDMC, LNC and LPC) and growth traits (FD_{growth}, which included MH and WD). Based on the literature available relating functional traits to ecological processes, CWM values used in our analysis were SLA, LDMC, LNC and WD.

3.2.2 Statistical analysis

We used mixed effects models to verify the effect of individual or combined predictors ($Richness_{spp}$; CWM values for SLA, LDMC, LNC and WD; and FD indexes – FD_{leaf} and FD_{growth}) on each ecological process. We normalized values per site (using method "standardize" in the *vegan* package), before running the analysis, in order to reduce variability between sites; and we included treatment (restoration vs. reference forest) as a random effect in the model, in order to control for possible lack of independence between sampling units within each treatment or for differences related to the community *a priori* characteristics. All traits that possibly have an effect on the ecological processes were inclued in the global model. To evaluate which predictors most influence each ecological process we used model averaging to calculate average parameters. This model averaging approach avoids ignoring models with similar fits. Based on their AIC scores, models are assigned a weight. This weight is then used to obtain a final average model using all fitted parameters averaged over the full set of models (Visser *et al.* 2016). We calculated average parameters over all models having AIC weights > 0 (Grueber *et al.* 2011; Visser *et al.* 2016). Valid models were considered the ones with $\Delta AIC < 2$.

Most of the variables were transformed prior to the analysis for normality distribution purposes: we used log-transformation for AGB, litter stock, decomposition and $\text{Litter}_{\text{CN}}$; square-root for understory abundance, $\text{Richness}_{\text{spp}}$, FD_{leaf} and $\text{FD}_{\text{growth}}$; and box-cox for LA, LDMC and MH. All analysis were performed in R (R Core Team 2016), using the packages *bbmle*, *MASS*, *MuMin*, *nlme* and *vegan*.

3.3 Results

Results from model averaging are presented in Table 3.1 and the importance of each variable in the models is shown in Table 3.2. We did not find any strong correlations between our parameters (Table S3.1). The average model for understory abundance was based on 3 models and contained variables LDMC, LNC and $\text{Richness}_{\text{spp}}$. Understory abundance increased with all three variables. For AGB, the average model was based on 3 models that included LDMC, WD and $\text{Richness}_{\text{spp}}$. AGB increased with LDMC and species richness, but decreased with WD. The average model for litter stock was based on only 1 model: litter stock decreased with SLA. The average model for detritivory, decomposition and Soil_{CN} was based on 2 models, which included the Null model. Finally model average for $\text{Litter}_{\text{CN}}$ was based on 3 models that included LNC, LDMC and $\text{FD}_{\text{growth}}$. Both traits had a negative effect on C:N values, while $\text{FD}_{\text{growth}}$ showed a positive effect.

Table 3.1. Average models with ΔAIC < 2 for each measure of ecological process, indicating the importance of each parameter: leaf dry matter content (LDMC), leaf nitrogen content (LNC), specific leaf area (SLA), wood density (WD), functional diversity for leaf (FD_{leaf}) and growth traits (FD_{growth}) and tree species richness ($Richness_{spp}$).

Parameter	**AICc**	**ΔAIC**	**Weight**
Understory abundance			
LDMC + LNC	239.68	0.00	0.25
LDMC + $Richness_{spp}$	239.97	0.29	0.22
LDMC	241.63	1.95	0.09
Aboveground biomass			
LDMC	196.85	0.00	0.29
LDMC + WD	197.08	0.23	0.26
LDMC + $Richness_{spp}$	198.12	1.27	0.16
Litter stock			
SLA	245.26	0.00	0.45
Detritivory			
(Null)	242.14	0.00	0.35
WD	243.36	1.22	0.19
Decomposition			
(Null)	249.33	0.00	0.25
FD_{leaf}	249.63	0.30	0.22
$Litter_{CN}$			
LNC	222.99	0.00	0.24
LDMC + LNC	223.53	0.53	0.18
LDMC + FD_{growth}	224.35	1.35	0.12
$Soil_{CN}$			
FD_{leaf}	254.56	0.00	0.18
(Null)	254.76	0.20	0.16

Table 3.2. Variable importance and estimate coefficients for each predictor variable (see parameter abbreviations in Table 3.1).

Variable	Variable importance	Estimate coefficient
Understory abundance		
LDMC	1.00	0.462
LNC	0.51	0.122
Richness$_{spp}$	0.43	0.098
Aboveground biomass		
LDMC	0.98	0.329
WD	0.38	-0.063
Richness$_{spp}$	0.27	0.041
Litter stock		
SLA	1.00	-0.464
Detritivory		
WD	0.32	-0.061
Decomposition		
FD$_{leaf}$	0.47	0.111
Litter$_{CN}$		
LNC	0.88	-0.248
LDMC	0.40	-0.084
FD$_{growth}$	0.31	0.064
Soil$_{CN}$		
FD$_{leaf}$	0.49	-0.125

3.4 Discussion

Here we presented important evidence on the effect of species richness and functional traits on a variety of ecological processes in subtropical forest ecosystems. They support the evidence that biodiversity effects on ecological processes, which may influence ecosystem services, occur through species characteristics rather than just species number. All of the ecological processes analyzed in this study responded strongly to functional traits (via CWM or FD) rather than to tree species richness. Although we found many significant relationships, some processes related to the soil layer (decomposition, detritivory and soil quality) did not respond to plant traits as initially expected, indicating that other factors, such as soil fauna composition and abundance, might be playing an important role.

3.4.1 Community functional composition

Variables related to community functional composition (CWM) had important effects on several ecological processes included in our study. The most frequent trait was LDMC, which had a positive effect on understory abundance and AGB and a negative effect on $\mathrm{Litter}_{\mathrm{CN}}$. LDMC is related to the average density of leaf tissues and leaves with higher values of this trait tend to be relatively tough and resistant to physical hazards (Perez-Harguindeguy *et al.* 2013). LDMC was found to be a good predictor of aboveground net primary production, showing a negative association with biomass production (Smart *et al.* 2017). Higher values of LDMC in communities are usually associated to advanced stages of forest succession, especially where evergreen species are dominant (Boukili & Chazdon 2017). In our study LDMC did not strongly correlate with basal area (results not shown) and only showed a moderate correlation with the community potential maximum height of species (r=0.49; Table S3.1). We certainly have some older community plots associated with higher LDMC values, since AGB was also predicted by this trait. Thus older and richer sites associated with higher values of LDMC have higher understory abundance and AGB. This explanation would also hold for the negative association between LDMC and $\mathrm{Litter}_{\mathrm{CN}}$ as older and more diverse communities would promote higher litter quality, thus decreasing litter C:N values.

Litter nitrogen content was positively associated with understory abundance and negatively associated with $\mathrm{Litter}_{\mathrm{CN}}$. The effect of LNC on $\mathrm{Litter}_{\mathrm{CN}}$ is straightforward since litter nitrogen content originates from its availability in canopy tree leaves: higher values of LNC in the canopy will reduce C:N values in litter. The association between LNC and understory abundance could be related to the presence of deciduous species that usually present higher values of LNC and low LDMC (Reich & Oleksyn 2004). The canopy of seasonal forests in the region is composed of a mix of evergreen and deciduous species, and the local-scale impact of these deciduous species could explain the results found here. Additionally, since deciduous species drop part of their leaves every season, it would enhance light availability in the understory, promoting increasing seedling abundance.

Specific leaf area was negatively associated with litter stock. This trait is often positively correlated to growth rates and negatively associated with leaf longevity and carbon investment in secondary compounds, such as tannins or lignin (Perez-Harguindeguy *et al.* 2013). Also SLA can be associated with LNC (Perez-Harguindeguy *et al.* 2013), which would imply in higher quality and faster decomposition (García-Palacios, Maestre & Milla 2013). So litter showing higher SLA values would promote faster rate of transformation and less accumulation when reaching the soil surface. It is important to note that litter accumulation is also influenced by vegetation structure, such as tree abundance and canopy cover (Mota & Torezan 2013), and by the presence of deciduous species, which can affect the amount of litter remaining in the soil.

Finally WD had a negative effect on AGB. WD relates to defense against decay, mechanical strength and growth-survival trade-off (Chave *et al.* 2009; Larjavaara & Muller-Landau 2010; Rüger *et al.* 2012) and is usually positively related to late successional species. WD is commonly negatively related to AGB increments, but is effect on AGB stocks is still uncertain (Finegan *et al.* 2015). In subtropical forests in China, WD showed a positive effect on AGB (Ali *et al.* 2017), but AGB estimates were based on allometric equations that contained WD as one of the predictors. On the other hand, in a recent study in tropical forests in Bolivia, Brazil and Costa Rica, AGB showed a negative association with WD, although this result was not statistically significant (Finegan *et al.* 2015). As in this last study, our estimates did not include WD as a predictor of AGB and we found a similar negative association. WD seems to show inconsistent trends when associated with AGB stocks, reflecting local site-specific factors that might be affecting functional composition (Boukili & Chazdon 2017).

3.4.2 Traits and species diversity measures

In contrast with the community mean values described above, litter nutrient availability ($Litter_{CN}$) was positively associated with FD_{growth}. We could not find a strong explanation for the positive effect of FD_{growth} on $Litter_{CN}$. We believe that this relation might be indicating an association between sites that show greater variability in plant height and WD and consequently higher $Litter_{CN,}$ probably mediated by species composition. Although decomposition and $Soil_{CN}$ could be influenced by FD_{leaf}, the Null model was among the valid models. This indicates that other factors not accounted in our data may be responsible for the variation in decomposition and soil quality.

Tree species richness ($Richness_{spp}$) had a positive effect on seedling abundance and AGB. Increased species richness in the canopy can be associated with greater abundance of seedlings and saplings in the understory (Suganuma & Durigan 2015). Species richness on both canopy and understory, as well as understory density, is expected to increase with forest age (Suganuma & Durigan 2015) as new species are able to colonize. Many additional factors can affect seedling density/diversity, such as litter depth and canopy openness (Molofsky & Augspurger 1992; Dupuy & Chazdon 2008). As for AGB, tree species richness has been shown to be positively related to productivity in global forests (Liang *et al.* 2016), which might explain higher AGB values in species-rich sites.

3.4.3 Considerations on ecological theory

Our results suggest that functional traits are more important than species richness in modifying ecological processes. Species richness did not show a strong, primary effect on the ecological processes studied here, but it did however present an effect when associated with other functional trait variables. This result supports growing evidence associated with BEF research, which states that biodiversity effects on decomposition occur through species characteristics, e.g. via functional trait composition (Díaz *et al.* 2006). Although studies have shown a positive effect of species diversity on productivity (Cardinale *et al.* 2007) and litter production (Scherer-Lorenzen, Bonilla & Potvin 2007), many studies show a more important effect of functional traits (diversity and CWM), rather than species richness, on different ecosystem processes (e.g. decomposition; Scherer-Lorenzen *et al.* 2007; Scherer-Lorenzen 2008), as found in our study.

Another important result is that both community level trait values (CWM) and functional diversity measures (FD) play a role in modifying ecological processes. Our results suggest that processes more associated with plant dynamics (such as natural regeneration, biomass stock and litter quality) respond to community level measures and are therefore associated with mass-ratio theory (Grime 1998). On the other hand, soil and soil fauna related processes (such as decomposition and soil quality) might be more closely related to functional diversity measures, which supports niche complementary effects. Additionally, these measures related to soil processes might interact with soil fauna composition (not accounted in this study) increasing explanation for changes in these processes. Many studies support the evidence to mass-ratio rather than niche complementarity hypothesis (de Bello *et al.* 2010) indicating a stronger effect of the dominant trait values (CWM). However, when CWM effects are poor, then functional diversity might play an important role (Díaz *et al.* 2007). Our results support the growing evidence of the effect of functional traits on ecological processes, contributing to study on the functionality of forest ecosystems. It also provides evidence for the use of functional traits in the monitoring of forests undergoing restoration and to evaluate the recovery of ecosystem functioning.

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3.6 Supplementary material

Table S3.1. Correlation matrix between all the variables included in the study. Abbreviations refer to: ecological processes – understory (UND), aboveground biomass (AGB), litter stock (LIT), detritivory (DET), decomposition (DEC), litter and soil C:N ratio (CNL and CNS); and species or functional measures – tree species richness (rich), leaf area (LA), specific leaf area (SLA), leaf dry matter content (LDMC), leaf nitrogen and phosphorus content (LNC and LPC), maximum height (MH), wood density (WD) and functional diversity for leaf ($\mathrm{FD}_{\mathrm{leaf}}$) and growth traits ($\mathrm{FD}_{\mathrm{growth}}$).

	UND	AGB	LIT	DET	DEC	CNL	CNS	rich	la	sla	ldmc	lnc	lpc	mh	wd	$\mathrm{FD}_{\mathrm{leaf}}$	$\mathrm{FD}_{\mathrm{growth}}$
UND	1.00																
AGB	0.28	1.00															
LIT	-0.08	-0.23	1.00														
DET	-0.34	-0.45	0.00	1.00													
DEC	0.14	0.36	-0.31	-0.18	1.00												
CNL	-0.36	-0.47	0.22	0.32	-0.32	1.00											
CNS	-0.05	-0.20	0.04	0.18	-0.26	0.10	1.00										
rich	0.34	0.34	-0.30	-0.07	0.12	-0.25	-0.10	1.00									
la	0.03	0.14	0.13	-0.14	0.29	-0.10	-0.16	0.22	1.00								
sla	0.19	0.24	-0.46	-0.16	0.26	-0.30	-0.25	0.45	0.09	1.00							
ldmc	0.49	0.61	-0.16	-0.36	0.25	-0.44	-0.21	0.23	-0.15	0.10	1.00						
lnc	0.25	0.19	-0.23	0.02	0.16	-0.36	-0.17	0.46	0.10	0.67	0.01	1.00					
lpc	-0.20	-0.32	0.05	0.28	-0.14	0.11	0.08	-0.09	-0.08	0.23	-0.56	0.43	1.00				
h	0.31	0.46	-0.10	-0.26	0.32	-0.42	-0.27	0.30	0.16	0.11	0.49	0.25	-0.14	1.00			
wd	0.13	0.02	0.26	-0.24	0.07	-0.01	-0.14	-0.28	0.10	-0.39	0.32	-0.48	-0.51	0.22	1.00		
$\mathrm{FD}_{\mathrm{leaf}}$	0.05	0.03	-0.17	-0.04	0.26	-0.16	-0.27	0.49	0.57	0.52	-0.22	0.52	0.27	0.17	-0.22	1.00	
$\mathrm{FD}_{\mathrm{growth}}$	-0.18	-0.28	-0.12	0.21	-0.05	0.30	-0.03	0.24	0.13	0.24	-0.35	0.21	0.36	0.00	-0.22	0.58	1.00

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CAPÍTULO 4

Predizendo comunidades em restauração baseado no ecossistema de referência utilizando uma abordagem de atributos funcionais

Predicting restored communities based on reference ecosystems using a trait-based approach

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Predicting restored communities based on reference ecosystems using a trait-based approach

Abstract

Ecological restoration should focus, not only on species composition, but also on the ecological functions provided by the ecosystem, mirroring the characteristics found in the reference site. In this context, plant functional traits could help to achieve this goal, as they directly affect ecosystem processes. Thus, modeling species composition based on species functional traits could provide ways to make predictions about future communities and to assess the functioning of the ecosystem. In order to evaluate how different restored communities are from their reference ecosystem, we used a trait-based modeling approach that predicts relative abundances of a community based on the functional composition of the reference ecosystem. We surveyed adult trees in the canopy and seedlings in the understory in both reference and 10 year-old restoration sites in two different locations in South of Brazil to gather information of species composition and their relative abundances. Functional composition was based on information of leaf traits for all species included in the survey. We applied the model on two different components: canopy and understory species. We found differences in functional composition between the restored communities and the reference sites, indicating that the ten-year old restored forests are still not similar to the reference ecosystem. Both the observed and the predicted understory communities were more similar to the reference ecosystem than the observed canopy communities. It indicates that species that established after restoration interventions have functional composition closer to the reference ecosystem than the set of species initially selected for planting. Modeling the community based on functional trait composition coupled with long-term monitoring of sites undergoing restoration would enable a better evaluation of restoration trajectories and management needs to modify ecosystem functions towards values found in reference sites. Restoration should focus on the recovery of functional composition, which would provide a better set of resources for organisms and promote changes in ecosystem processes.

*Keywords***:** Ecosystem process; functional ecology; functional traits; natural regeneration; subtropical forest.

4.1. Introduction

Restoration ecology aims to recover ecosystems with the goal of creating a natural ecosystem that is both functional and that provides habitat for many different organisms (SER 2004; Aronson *et al.* 2006). In this context, it is usually targeted to reach reference conditions, which is a preserved ecosystem that resembles the one that occurred prior to degradation (SER 2004). For forest restoration, this usually means planting the same native species found in the reference sites (Lamb 2005; Rodrigues *et al.* 2009), with the objective of creating a more similar community in regards to species composition. Although planting a large number of species increases values of biodiversity (Sampaio, Holl & Scariot 2007), it is not ensured that all features observed in the restored site will resemble the mature forest.

The recovery of species composition and vegetation structure towards mature forests does not necessarily follow a predictable trajectory (Norden *et al.* 2015) and long term monitoring is required to evaluate how different parameters change in time (Suganuma & Durigan 2015). Many studies show a slow recovery of floristic and structural vegetation parameters along the succession process (Liebsch, Marques & Goldenberg 2008; Dent, Dewalt & Denslow 2013), which leads to uncertainties in determining the success of restoration projects. Good indicators of restoration success are a central focus in ecological restoration. More recently, many authors have suggested a set of parameters that would be good predictors of vegetation recovery (Reid 2015; Suganuma & Durigan 2015; Brancalion

& Holl 2016). Among them, basal area and seedling abundance were suggested (Suganuma & Durigan 2015), but they disregard the contribution of species composition to the increased similarity towards reference sites, which is an important goal in ecological restoration (Reid 2015). Finally, Brancalion & Holl (2016) suggested that a combination of basal area and abundance with compositional and/or functional parameters would be a more reliable measure to evaluate restoration success. We agree that using functional measures would help in determining whether the restoration has been successful since they relate more directly with ecological processes in the ecosystem level. Thus focus on ecosystem functioning could provide ways to determine if restored sites are performing well irrespectively of species composition, offering conditions for biotic interactions among different groups of species and maintaining ecosystem processes.

This emphasis on ecosystem functions has driven a growing focus on species characteristics (e.g. functional traits) rather than its identity (Diaz & Cabido 2001; Garnier *et al.* 2004). A broad definition considers a functional trait as an organism's trait that affects individual or species fitness via effects on growth, reproduction and survival (Violle *et al.* 2007), responding to environmental conditions or affecting ecosystem properties (Lavorel 2013). A number of recent studies indicate that trait composition and different functional diversity measures can affect ecosystem processes in a number of ways (Diaz & Cabido 2001; Garnier *et al.* 2004; Kazakou *et al.* 2006). Decomposition is negatively affected by leaf lignin content and dry matter content (LDMC) and positively affected by nitrogen (Freschet, Aerts & Cornelissen 2012); soil fertility is influenced by LDMC and leaf litter nitrogen (Laughlin *et al.* 2015); above-ground biomass increments and carbon sequestration can be predicted by specific leaf area – SLA (Finegan *et al.* 2015) and wood density (Larjavaara & Muller-Landau 2010); and seedling survival is increased by seed mass (Moles & Westoby 2004). Therefore, given the goal of restoration ecology, instead of just trying to increase species richness, one should look to the different traits related to photosynthetic performance, growth and dispersal of the species selected for planting. Many databases for plant traits are available and provide data for many species across the globe (e.g. Kattge *et al.* 2011). An important step when working with ecosystem functioning is trait selection (Petchey & Gaston 2006), which consists in including parameters that really affect ecosystem ("effect traits", Lavorel & Garnier 2002) and that are not just a response to environmental conditions. Therefore, measuring and evaluating traits that most affect ecosystem properties could be a tool to understand the community dynamic and to guide restoration in achieving targeted functional reference conditions.

Additionally, as species traits affect how species interact and influence the assembly processes that occur in a community (HilleRisLambers *et al.* 2012), they are believed to drive the way biodiversity affect ecosystem properties (Millennium Ecosystem Assessment 2005). The possibility of using species traits that most affect ecosystem processes (Suding *et al.* 2008) could allow the prediction of a community that would promote fast development of a given ecosystem process, based on values from desired targets or reference sites. Recently, several models have been proposed to predict communities based on target ecosystems or functional values (Laughlin *et al.* 2012). In the field of ecological restoration, this approach could be used by practitioners when selecting the most suitable set of species to be planted in order to increase or slow a specific ecosystem process in a degraded site (e.g. decomposition or nutrient cycling; Laughlin 2014). It could also be used for theory driven studies in restoration ecology aiming to understand community assembly processes based, for example, on niche complementarity or resistance to species invasion (Funk *et al.* 2008; Laughlin 2014). The functional trait-based approach can bring important information to restoration ecology (Laughlin 2014), especially when the goal is to assess functionality (Diaz & Cabido 2001).

In this study, we applied a recently proposed trait-based model to predict a community based on the functional composition from the reference ecosystem (Laughlin 2014). We based our analysis on the expectation that restoration sites should achieve ecosystem characteristics similar to the reference site (SER 2004) and that monitoring of functional values could show how distant restored communities are from their reference. We aimed to evaluate if the functional composition from forest sites undergoing restoration resembles the characteristics found in the reference ecosystem (remnant forests). More specifically, we aimed to analyze how similar with regards to functional composition are the canopy and the understory communities of restored sites from reference ecosystems by applying a trait-based modeling approach. We then compared the results from both models (the predicted communities based on canopy and the understory) with the observed communities in order to evaluate possible trajectories towards mature forests. Applying the model on both canopy and understory species could provide an interesting perspective on present and future conditions from the restored sites, pointing out to successional trajectories. We focused on the composition of the restoration site from both canopy and understory trees, using as reference the canopy of the remnant forest. Prior to the modeling, we first compared restoration and reference sites in terms of their community-level trait means to highlight the existing differences between these communities and then applied the model to generate predicted communities that meet the range found in the reference ecosystem. The use of trait-based ecology could be an interesting tool for practitioners, due to its capacity to predict communities that are functionally more similar to the targeted ecosystem (Laughlin 2014). Such modeling approaches could be applied both in the start of the restoration project (predicting abundances for each species available for planting) and after a few years of recovery (as in the present study), with the goal of monitoring the successional trajectory of recovery and using adaptive management to assist restoration (e.g., species removal and/or management of natural regeneration).

4.2. Material and methods

4.2.1 Study site and sampling

We performed the study in two forest restoration sites in the South of Brazil (Site 1 – Cachoeirinha: 29º52'S 51º05'W; and Site 2 – Canela: 24º22'S 50º43'W). In each site we performed the survey in both treatments: restoration and reference forest. The type of ecosystem in Site 1 is a semi-deciduous riparian forest. The site had a history of cattle grazing and is inserted in an anthropogenic, urban and disturbed matrix. Restoration practices focused on planting native tree species (ca. 23 species) in order to increase the width of the riparian forest. Site 2 is a semi-deciduous forest that used to be a eucalyptus plantation that was clear-cut. Restoration was also based in planting native species (ca. 34 species) to accelerate ecosystem recovery, and the matrix that surrounds the site is a mix of early to advanced successional-stage forests. After the actions of restoration, both sites were left to recover for approximately 10 years. Reference sites are located adjacent to restoration sites and we assumed that they represent the composition and structure of previous forests of each restoration system. In order to examine the functional composition of restoration and reference sites we sampled 15 plots (100 m^2 in size) per treatment and identified each species inside the plot. The main sample unit (100 m^2) was used to survey adult trees (diameter at breast height (DBH) ≥ 5 cm). Seedlings/saplings (height ≥ 30 cm and DBH < 5 cm) were sampled in three subsamples (4 m^2) inside each main sample unit. Adult trees in restoration sites consisted mostly of planted individuals. Species and family names followed Sobral *et al.* (2006) and APG IV (2016).

Functional trait data from each species was based on the database from the Plant Ecology Lab at the Universidade Federal do Rio Grande do Sul (LEVEG/UFRGS, Brazil), which follows the protocol proposed by Perez-Harguindeguy *et al.* (2013). This database is a regional compilation and includes most of the tree species found in the state of Rio Grande do Sul, Brazil. Leaf traits used in the analysis were leaf area (LA, mm^2), specific leaf area (SLA, mm^2 mg^{-1}) and leaf dry mass content (LDMC, mg g^{-1}), for which we were able to gather, in our trait database, information on intraspecific variability. For each trait, a minimum of five individuals per species was sampled. We selected these traits because they are thought to have large influence on ecosystem processes such as productivity, decomposition and nutrient cycling: LA affects water balance and nutrient cycling, given its influence on leaf energy (Farquhar, Buckley & Miller 2002; Díaz *et al.* 2016); SLA can positively affect decomposition (Garnier *et al.* 2004) and carbon sequestration (Finegan *et al.* 2015); and finally, LDMC can slow decomposition rates (Garnier *et al.* 2004; Freschet, Aerts & Cornelissen 2012) and affect soil fertility (Laughlin *et al.* 2015). These traits represent important facets of the leaf economics spectrum, a known gradient between fast and slow-growing species that can be associated with ecosystem processes and successional trajectories (Wright *et al.* 2005; Reich 2014). Mean values of each trait for each species are available in Table S4.1.

4.2.2 Statistical analyses

Analyses were based on a recently proposed trait-based model (Laughlin *et al.* 2012; Laughlin 2014) in which values from functional traits from reference sites are the targets for the predicted community. The model estimates the relative abundances of species (in our example, a subset from the species planted in the restored site) that meet the values of functional traits found in the target ecosystem (reference ecosystem; Fig. 4.1). The model is fitted using a Bayesian framework that includes inter- and intraspecific trait variation and covariation (Laughlin *et al.* 2012). The potential relative abundance of each species is estimated by the joint probability of (i) the species given the trait distributions and the environment (target ecosystem), and (ii) the trait given the environment (Laughlin 2014). We used non-informative priors on species abundance, assuming that each and every species is equally likely to occur. The posterior distribution was obtained based on Monte Carlo Markov Chains (for further details see Laughlin *et al.* 2012; Laughlin 2014; Cadotte *et al.* 2015). To calculate the constraints from the target ecosystem we used a matrix of all individuals sampled in the reference forest (337 and 280 individuals in Site 1 and 2, respectively), with species-level values for each leaf trait: LA, SLA and LDMC. These constraints contain the variability found in the reference site. All trait values were log-transformed prior to the analysis. To account for trait variability within species, we used a matrix of species-level trait values with intraspecific variability for each species (that includes variation from 5 to 26 individuals per species). We calculated the relative abundances of the predicted community based on the 15 most abundant species from the restored community, given the fact that the most dominant plants are expected to be the ones with higher influence in ecosystem properties (*mass ratio hypothesis,* Grime 1998). The output of the analysis (using the two matrices described above) shows the relative abundance of each species in the predicted community given trait inter- and intraspecific variability and also ecosystem variability (Fig. 4.1). Species composition of the restored site was based on two strata: (1) canopy species – that is all adult trees (DBH ≥ 5 cm) sampled in each sample unit, which consists mostly of planted species but also of the ones that naturally colonized the former degraded site; and (2) understory species – which are all tree species (height ≥ 30 cm and DBH < 5 cm) that naturally colonized the restored site after restoration practices. No special attention was given to floristic composition in the reference site, this identification was only important to set the constraints of the target functional composition.

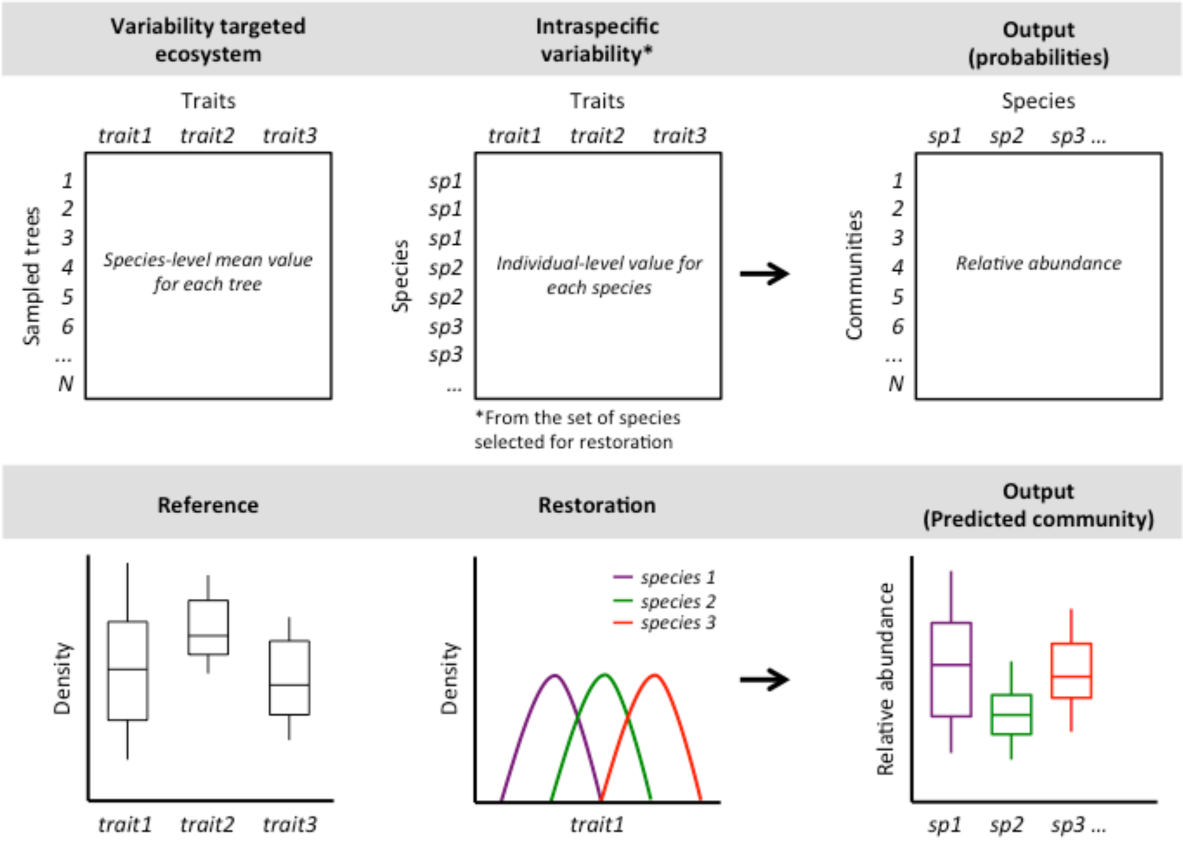

Figure 4.1. Data matrices used to generate the predicted communities. The modeling approach uses first the distribution of each trait in the targeted ecosystem, which shows the variability in the reference ecosystem (left). Then it calculates the intraspecific variability for the set of species selected for restoration, computing the trait distribution for each species (center). The output (right) shows the relative abundance of each species (from the set of species selected for restoration) in the predicted community. A more thorough description of the statistics used in the model is given in Laughlin *et al.* (2012) and Cadotte *et al.* (2015).

We used Principal Component Analysis (PCA) to evaluate the functional trajectory patterns towards the reference forest. We performed PCA on all five communities (observed canopy from restoration, observed understory from restoration, predicted canopy community, predicted understory community and reference forest) described by their leaf trait community weighted means (CWM), in a number of 15 sample units per treatment. We used PERMANOVA to evaluate significant differences between treatments. All analyses were performed in R (R Core Team 2016). The trait-based model was performed using the packages *MASS* and *mclust*, following the script described in Laughlin (2014). Values of CWM were calculated using the *FD* package and we used the package *vegan* for the PERMANOVA test.

4.3. Results

4.3.1 Trait differences between restored and reference communities

Differences in CWM values for each trait between the observed canopy community and the reference ecosystem were statistically significant only for Site 1 (Table 4.1). Values of SLA and LDMC were higher in the reference ecosystem when compared to the observed canopy. For Site 2, differences between CWM values across traits were not statistically significant (Table 4.1) and showed high variability within treatments, as shown by the values of standard deviations in Table 4.1.

4.3.2 Model prediction for canopy species

The predicted community based on the model for canopy species resulted in a community distribution with lower dominance of the most abundant species. In Site 1, species that were most abundant in the observed restored community (*Psidium cattleyanum* and *Schinus terebinthifolius*) had lower values in the predicted community, whereas very low abundant species showed higher values (Fig. 4.2a and 4.2c), projecting a more equitable community. According to the model prediction, the most abundant species (with relative abundances higher than 10%) were *Apuleia leiocarpa*, *Vitex megapotamica*, *Allophylus* *edulis* and *Eugenia uniflora*. In Site 2, the predicted community also showed a more equitable species distribution when compared to the restored community (Fig. 4.3a and 4.3c). Species that had low abundance in the observed community were very abundant in the predicted community (especially *Casearia sylvestris*, *Solanum pseudoquina* and *Bauhinia forficata*; right side of Fig. 4.3c). However, some of the most dominant species in the observed restored community showed higher abundance also in the predicted community (*Inga marginata* and *Nectandra megapotamica*). The most abundant species in the predicted community were *I. marginata*, *N. megapotamica*, *Luehea divaricata* and *B. forficata*.

Table 4.1. CWM values (± SD) for leaf area (LA), specific leaf area (SLA) and lead dry matter content (LDMC) per treatment in each study site (Site 1 and 2). Significant differences between reference and observed canopy values are shown by the p-value in bold.

	Reference	Observed canopy	p-value
Site 1			
LA	11.32 (3.89)	12.35 (4.22)	0.49
SLA	11.48 (0.86)	9.78 (2.51)	**0.018**
LDMC	403.27 (18.29)	390.54 (14.89)	**0.045**
Site 2			
LA	31.09 (29.78)	18.35 (5.41)	0.12
SLA	13.20 (3.20)	11.68 (0.81)	0.08
LDMC	386.64 (44.26)	382.59 (24.00)	0.77

4.3.3 Model prediction for understory species

Although many species found in the understory are new colonizers (i.e., only observed as young trees), some species growing in the canopy layer were also present in the understory (colored bars in Figs. 4.2b and 4.3b). In Site 1, the relative abundance from the natural regeneration showed a higher contribution of *M. coriacea*, but included many species present in the canopy layer, such as *P. myrtifolia*, *E. uniflora*, *Mimosa bimucronata*, *P. cattleyanum*, *L. divaricata*, *S. terebinthifolius* and *A. edulis* (Fig. 4.2b). In Site 2, the two most abundant species were *C. vernalis* and *N. megapotamica* (Fig. 4.3b), but *O. puberula*, *C. sylvestris*, *I. marginata* and *M. coriacea* should also be mentioned. Many species found in the understory were not present in the canopy layer (grey colors in Fig. 4.2b and 4.3b) indicating that there is colonization of new species from adjacent sites. In both sites, the community predicted for the understory layer (Fig. 4.2d and 4.3d) showed less dominance from one or two species, a similar pattern as the previous canopy prediction. In Site 1, the most abundant species in the predicted understory community were *E. uniflora*, *Erithroxylum argentinum*, *A. edulis* and *P. myrtifolia*. In Site 2, the most abundant species were *C. vernalis*, *I. marginata*, *Casearia decandra* and *Mollinedia shottiana*. It is important to note that some species ranked with higher abundance in the predicted understory community (Fig. 4.2d and 4.3d) were also abundant both in the observed restored understory (Fig. 4.2b and 4.3b) and the predicted canopy communities (Fig. 4.2c and 4.3c; see matching colors in plots).

4.3.4 Observed vs. predicted communities

Results from the PCA performed with leaf traits' CWM indicated that the predicted communities showed smaller variability in the ordination space and points were located inside the range of the observed communities (Fig. 4.4). Since these communities are modeled to achieve functional composition closer to the reference forest, based on the species used in the restored site, the values obtained tend to be intermediate between the reference and the observed restored community values. Differences between treatments were statistically significant for Site 1 ($F=5.99$; $p<0.001$) but non-significant for Site 2 ($F=1.22$; $p=0.31$). In Site 1 the observed communities differed from both the reference (canopy *vs*. reference, $F=4.00$, $p<0.05$; understory *vs*. reference, $F=5.14$, $p<0.05$) and its predicted communities (canopy, $F=4.52$, $p<0.05$; understory, $F=22.33$, $p<0.001$). Also, the predicted and the observed understory communities were closer to the reference than were the observed canopy communities from the reference (see group centroids in Fig. 4.4). In Site 1, the predicted understory communities had most of its points just over the main distribution of the reference (Fig. 4.4a). In Site 2, differences between treatments were not significant, but we can also see the observed canopy communities more distant from the other treatments (Fig. 4.4b).

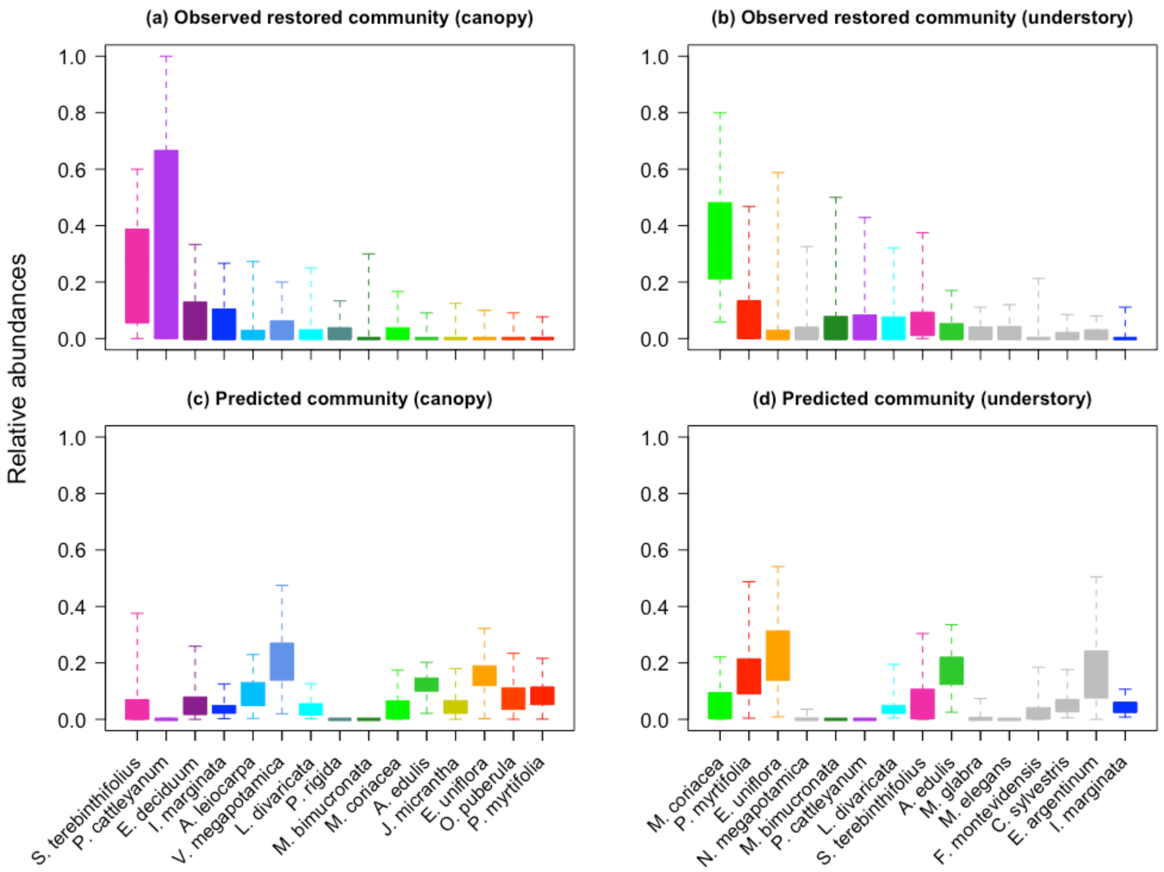

Figure 4.2. Relative abundances for the set of species found in Site 1. Plots show the relative abundances of: (a) the observed restored community for canopy species; (b) the observed restored community for understory species; (c) the predicted community based on data of leaf traits (LA, SLA and LDMC) for canopy species; and (d) the predicted community based on data of leaf traits for understory species. Plots (a) and (c) show canopy trees and (b) and (d) understory trees. Species are ordered based on decreasing values of the relative abundances found the observed restored community. Colors relate to each species found in the canopy layer and new colonizers in the understory layer are shown in grey.

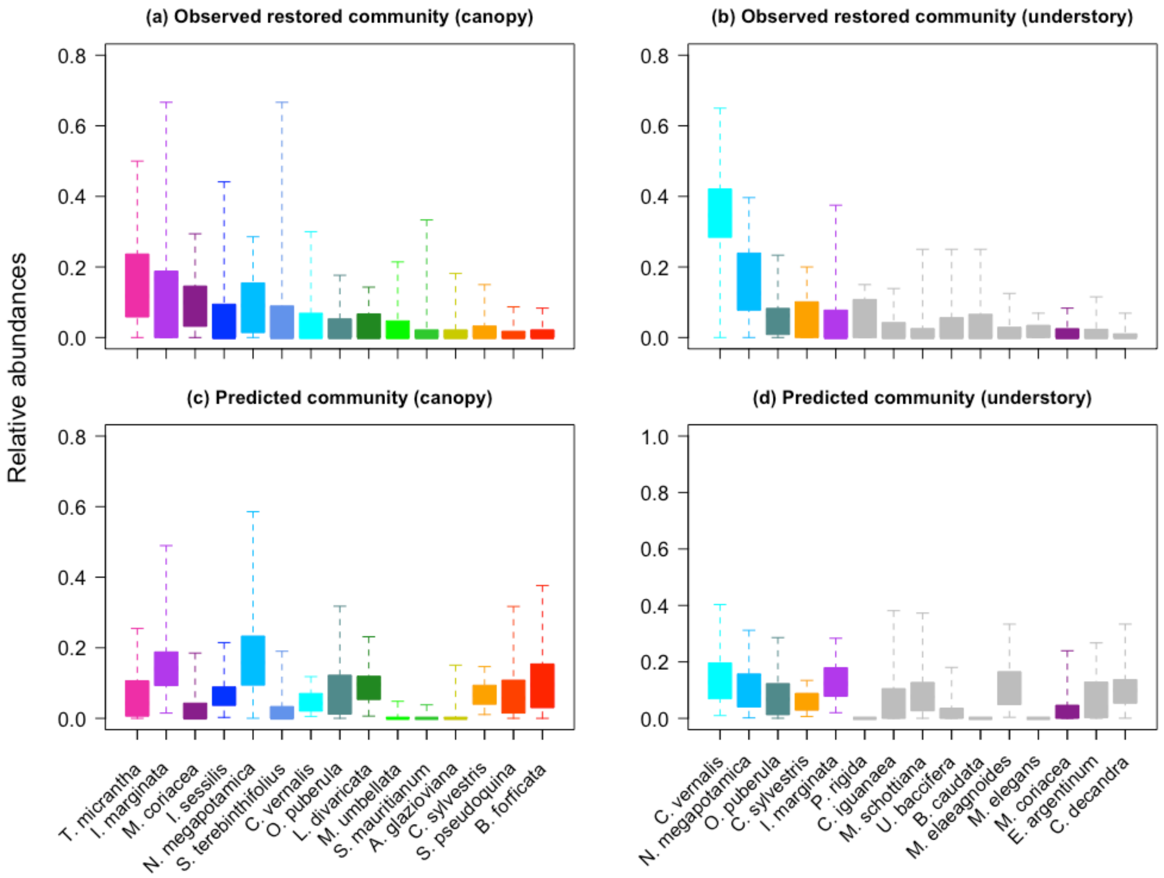

Figure 4.3. Relative abundances for the set of species found in Site 2. Plots show the relative abundances of: (a) the observed restored community for canopy species; (b) the observed restored community for understory species; (c) the predicted community based on data of leaf traits (LA, SLA and LDMC) for canopy species; and (d) the predicted community based on data of leaf traits for understory species. Plots (a) and (c) show canopy trees and (b) and (d) understory trees. Species are ordered based on decreasing values of the relative abundances found the observed restored community. Colors relate to each species found in the canopy layer and new colonizers in the understory layer are shown in grey.

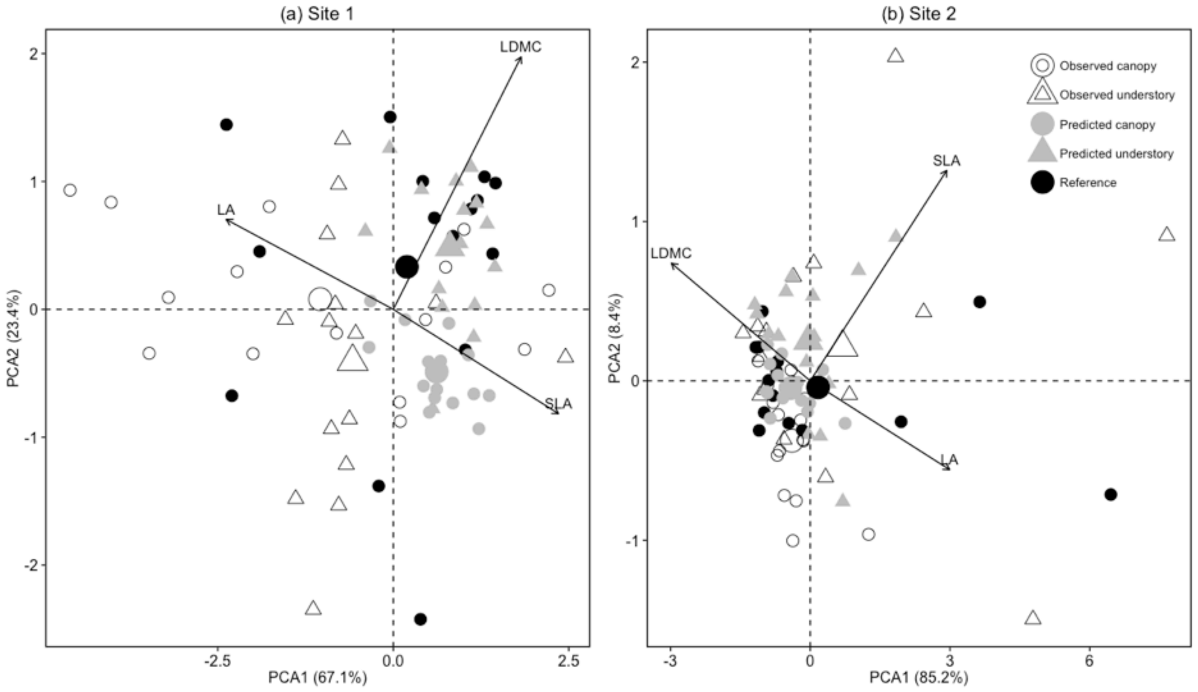

Figure 4.4. Results from Principal Component Analysis based on community-weighted means (CWM) for leaf traits (LA, SLA and LDMC), in Site 1 (a) and Site 2 (b). Colored circles indicate canopy treatments (reference, restoration and predicted communities) and triangles indicate understory treatments (restoration and predicted community). Large symbols indicate the centroid for each group.

4.4. Discussion

4.4.1 Monitoring functional trajectories

Our results show that this type of modeling could be an interesting tool to evaluate trajectories of vegetation growth taking into account functional components of the ecosystem. If long term monitoring is performed on restoration sites, it would be possible to verify if forest recovery is following a desired trajectory towards values found in the reference ecosystem, and to suggest management interventions if necessary. Even though ecosystem recovery follows unpredictable successional trajectories (Norden *et al.* 2015), we expect that functional characteristics found in restoration sites would converge to values found in mature forests (Dent, Dewalt & Denslow 2013). The predicted communities generated from our model differed from the observed restored community (for both canopy and understory): species that were more abundant in the predicted community were not the most abundant and in some cases showed a very low density in the observed community (Fig. 4.2 and 4.3). This suggests to the need of an adjustment in species relative abundances in order to achieve values similar to the reference ecosystem. According to this modeling, if the predicted values are similar to the observed values found in the restoration site then the community is following a desired trajectory and there is no need for management interventions. If, on the other hand, values observed in the restored site are very different from the prediction, even after a long period since the start of the restoration, than management interventions should be considered in order to direct restoration towards reference conditions. The pattern of functional composition found in our two study sites point out to different trajectories: results from Site 1 show a more scattered distribution of CWM values and the prediction from species relative abundances contrasts with the observed values found in the restoration site. This suggests that the observed restored community is distant from the reference ecosystem. If this pattern continues in the future, *i.e.* if the composition does not become more similar to what is found in the reference ecosystem, it could eventually suggest the need for management interventions in order to achieve restoration success. In Site 2, on the other hand, CWM values show a less scattered distribution, with many of the treatments overlapping. Also, the relative abundances from the predicted community show a more similar distribution to the observed values. This indicates that restoration is following a trajectory leading to the functional composition found in the reference ecosystem. It is important to highlight that both of our study sites are young (*ca.* 10 years old) and are still undergoing the initial stages of forest succession. The natural progress of vegetation growth might lead towards values found in the reference ecosystem. Monitoring these restored communities for a longer period is a key tool for project success (Suganuma & Durigan 2015), as practitioners can evaluate restoration trajectories and suggest, if necessary, management options.

When evaluating restoration trajectories, the canopy of the observed restored community represents the current condition of the forest. Its understory composition consists of the best available future scenario of what the community might resemble in a longer period of time, *i.e.* the group of species that will eventually reach the canopy of the forest and replace the existing species. A recent study in the Atlantic Forest (Suganuma, Assis & Durigan 2014) shows a decrease contribution of planted species to floristic composition along succession and a replacement by the regenerating species coming from seed sources near the restoration. In our study we used two scenarios (present/canopy and future/understory) and evaluated the predictions obtained from trait-based models. We found that the understory showed a functional composition closer to the reference than did the canopy communities. This indicates the potential of the understory in improving functional composition in the near future. If we consider the successional dynamics of vegetation growth, species that are able to establish at an early stage (pioneers and early successional) will eventually be replaced by species with different requirements and characteristics (late successional), more similar to what is found in mature forests. New colonizers coming from seed sources near the restoration site can increase biodiversity but more importantly can contribute to the increasing similarity with the reference ecosystem in terms of functional composition. This shows the importance of having forest remnants near restoration sites. In addition, these results highlight that in some cases species selection for planting might not reflect the characteristics found in the reference ecosystem, leading to a restored community that is not similar to its target, especially when natural regeneration is less intense. When planning the restoration project, species selection for planting needs to account for species characteristics in order to increase success of the establishment of both pioneers and secondary species. Also, long term monitoring will contribute to evaluating the necessity of management actions in order to ensure the right set of species established in the restored site.

The adjustment in functional composition in the predicted communities proposed by the model indicates that functions influenced by these different traits might not be performing as expected based on the values found in the target ecosystem. If the aim of the restored community is to resemble the characteristics of the reference ecosystem in terms of functionality (Chazdon 2008), then the objective of the restoration project has still not been achieved. Considering the most abundant species growing in the canopy and the understory of the observed restored sites, the model predicted an adjustment in species abundances in order to achieve functional composition similar to reference values (Fig. 4.4). Functional traits, especially leaf traits, have been shown to have significant effect on ecosystem processes (Díaz *et al.* 2007). For example, litter quality directly affects decomposition (Zhang *et al.* 2008; Freschet, Aerts & Cornelissen 2012): communities with high values of SLA and low values of LDMC show faster decomposition (Garnier *et al.* 2004; Laughlin *et al.* 2010) and lignin content has direct effect on litter decomposability (Aerts 1997; Freschet, Aerts & Cornelissen 2012). Additionally, functional traits, such as LDMC and litter nitrogen, have been shown to have strong effects on soil fertility (Laughlin *et al.* 2015). Thus modifying traits values in terms of species relative abundances (as proposed by the model) could alter the performance of ecosystem processes affected by these traits. In the case of Site 1, for example, the trait-based model suggested an increase in the relative abundances of the species *V. megapotamica* and *E. uniflora*. This change would increase the average value of SLA in the community, since these two species have higher values of this trait (12.3 and 14.0 mm^2 g^{-1}, respectively). Given that the most abundant species in the real observed community are *P. cattleyanum* and *S. terebinthifolius* and their average SLA is lower (5.2 and 9.5 mm^2 g^-

^{1}, respectively), the change in species relative abundances would increase mean values of SLA, increasing litter decomposition and reducing litter stock.

4.4.2 Conclusions

This type of modeling, based on ecosystem functional composition, is a tool that could be used both in the planning stage of the restoration project (when determining relative abundances of the species to be planted) and also during the monitoring stage, in order to evaluate trajectories towards the objective. Model predictions can provide the evaluation of trajectories of vegetation growth and, by suggesting adjustments in species composition, could help the work of practitioners, by making management more effective and directed towards the desired ecosystem. In our study we focused only on the most dominant species, because that is the group of species that mostly affect ecosystem processes (*mass ratio hypothesis*, Grime 1998). Species that are not very abundant could modify functions related to functional diversity and niche complementarity. It is also important to note that the number of traits included in the model will affect predictions. So traits that most influence a given ecosystem process (or processes) should be the ones to be included in the model. Managing the restored community based on the predictions (as discussed here) would be an interesting approach to evaluate the influence of functional traits on ecosystem processes (Funk *et al.* 2016) and how restoration actions could increase similarities towards reference ecosystems. Shifting the focus from plant diversity and species composition to ecosystem processes and the functions provided by biotic and trophic interactions (Fraser *et al.* 2015) could contribute to restoration projects and promote more resilient and self-sustaining communities in the long run.

4.5 Authors’ contributions

MFR and SCM conceived the idea of the paper, designed methodology and interpreted results. MFR collected the data, performed the analysis and led the writing of the manuscript. SCM critically and thoroughly revised the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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4.8 Supplementary material

Table S4.1 is shown in the next page.

Table S4.1. Species mean values for each leaf trait (LA: leaf area, SLA: specific leaf area and LDMC: leaf dry matter content). Indication of the site (1 or 2) and the stratum (canopy, understory or both canopy and understory) where the species was found is also provided.

Species	**Family**	**LA (mm^2)**	**SLA (mm^2 mg^{-1})**	**LDMC (mg g^{-1})**	**Site**	**Stratum**
Allophylus edulis	Sapindaceae	7.36	14.80	397.68	Site 1	Both
Apuleia leiocarpa	Fabaceae	4.85	14.67	370.10	Site 1	Canopy
Ateleia glazioviana	Fabaceae	6.79	19.64	300.00	Site 2	Canopy
Bauhinia forficata	Fabaceae	60.69	15.64	315.35	Site 2	Canopy
Boehmeria caudata	Urticaceae	51.43	54.02	173.47	Site 2	Understory
Casearia decandra	Salicaceae	6.57	15.68	503.51	Site 2	Understory
Casearia sylvestis	Salicaceae	15.16	12.21	414.22	Both	Both
Celtis iguanaea	Ulmaceae	12.72	10.34	406.81	Site 2	Understory
Cupania vernalis	Sapindaceae	23.20	11.35	408.53	Site 2	Both
Erythroxylum argentinum	Erythroxylaceae	9.66	10.48	439.26	Both	Understory
Erythroxylum deciduum	Erythroxylaceae	13.41	13.39	349.92	Site 1	Canopy
Eugenia uniflora	Myrtaceae	6.54	14.05	413.78	Site 1	Both
Faramea montevidensis	Rubiaceae	20.72	12.20	370.39	Site 1	Understory
Inga marginata	Fabaceae	15.43	11.93	427.48	Both	Both
Inga sessilis	Fabaceae	40.93	13.49	450.84	Site 2	Canopy
Jacaranda micrantha	Bignoniaceae	9.35	18.54	398.05	Site 1	Canopy
Luehea divaricata	Malvaceae	25.67	12.82	386.49	Both	Both
Matayba elaeagnoides	Sapindaceae	13.96	12.46	332.27	Site 2	Understory
Mimosa bimucronata	Fabaceae	0.18	16.43	458.08	Site 1	Both
Mollinedia elegans	Monimiaceae	2.63	8.39	317.49	Both	Understory
Mollinedia shottiana	Monimiaceae	33.36	23.64	283.65	Site 2	Understory
Myrcia glabra	Myrtaceae	24.45	7.41	359.15	Site 1	Understory
Mysine coriacea	Primulaceae	8.99	11.61	346.86	Both	Both
Myrsine umbellata	Primulaceae	64.17	6.65	372.59	Site 2	Canopy

Species	**Family**	**LA (mm^2)**	**SLA (mm^2 mg^{-1})**	**LDMC (mg g^{-1})**	**Site**	**Stratum**
Nectrandra grandiflora	Lauraceae	14.13	5.60	468.07	Site 1	Understory
Nectandra megapotamica	Lauraceae	9.58	10.21	430.39	Site 2	Both
Ocotea puberula	Lauraceae	15.66	9.84	413.05	Both	Both
Parapiptadenia rigida	Fabaceae	0.18	16.70	457.65	Both	Both
Prunus myrtifolia	Rosaceae	14.69	9.27	413.80	Site 1	Both
Psidium cattleyanum	Myrtaceae	19.07	5.21	375.73	Site 1	Both
Schinus terebinthifolius	Anacardiaceae	5.71	9.54	402.11	Both	Both
Solanum mauritianum	Solanaceae	29.72	17.53	206.80	Site 2	Canopy
Solanum pseudoquina	Solanaceae	16.66	14.84	304.36	Site 2	Canopy
Trema micrantha	Ulmaceae	14.35	10.70	344.17	Site 2	Canopy
Urera baccifera	Urticaceae	452.10	23.10	146.80	Site 2	Understory
Vitex megapotamica	Lamiaceae	10.81	12.29	399.74	Site 1	Canopy

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CONSIDERAÇÕES FINAIS E CONCLUSÃO

O presente trabalho apresentou um panorama geral dos processos ecológicos em florestas restauradas, indicando as variáveis de plantas que mais afetam o funcionamento do sistema. Uma vez que o monitoramento de áreas restauradas é muito focado em variáveis estruturais e florísticas, cada vez mais é necessária a aplicação de uma abordagem integrada, que considere tanto características e mecanismos da comunidade (estrutura e composição de espécies e atributos funcionais), quanto do ecossistema (processos ecológicos). Assim, é possível analisar o restabelecimento das funções do ecossistema após as intervenções de restauração, sua persistência ao longo do tempo, bem como os benefícios ecológicos propiciados pela atividade de restauração a curto, médio e longo prazo.

Os resultados apresentados ressaltaram a importância dos processos ecológicos em ecossistemas florestais, mas principalmente sua relevância na avaliação do funcionamento de áreas em processo de restauração. Ao longo dos quatro capítulos apresentados foram discutidos os principais processos ecológicos e medidas utilizadas no monitoramento de áreas em restauração e suas diferenças com relação a florestas preservadas, bem como as principais variáveis funcionais que explicam esses processos. Através de coletas realizadas em campo, de revisão bibliográfica e de modelagem de cenários com base nos dados coletados foram apresentadas diferentes facetas da dinâmica florestal no que diz respeito à recuperação da funcionalidade de ambientes em restauração.

No Capítulo 1, foi realizada uma revisão teórica sobre os principais processos ecológicos em ambientes florestais, contextualizando as relações entre os diferentes processos, padrões ao longo da sucessão e a provisão de serviços ecossistêmicos. Além disso, com o objetivo de avaliar de que forma esses processos vêm sendo monitorados em ambientes florestais, foram identificadas as principais variáveis de medida desses processos com base em revisão bibliográfica. Dessa forma, foi possível indicar como as variáveis medidas realmente informam sobre o desenvolvimento das áreas em restauração. Os processos mais medidos foram aqueles relacionados à ciclagem de nutrientes, seguido de resiliência do ecossistema, produtividade, relações hídricas e interações bióticas. O tempo desde o início da restauração foi um fator importante nos resultados obtidos com relação ao afeito da restauração nos processos ecológicos: mais resultados positivos nos processos ecológicos foram obtidos após 15 anos das intervenções. Além disso, se o monitoramento não for realizado com uma certa frequência ao longo do tempo, de modo a verificar modificações nos processos, é indicado comparar os resultados com áreas de referência. Os resultados indicaram que os processos podem demorar um período mais longo para se recuperar e que as ações de restauração promovem mudanças nos processos ecológicos que são importantes para a funcionalidade do ecossistema.

No Capítulo 2, o foco foi na utilização de uma abordagem integrativa que une parâmetros estruturais, florísticos, funcionais e de processos ecológicos para comparar sítios de restauração e suas respectivas florestas de referência. Foram coletados dados referentes a área basal, altura, número de indivíduos nas parcelas, bem como informações sobre a regeneração natural, biomassa de folhas, decomposição, detritivoria, qualidade da serapilheira e do solo. Além disso, foram coletados dados sobre a composição funcional das espécies amostradas, incluindo atributos foliares, reprodutivos e de crescimento. Os resultados indicaram que as áreas em restauração apresentam diferenças com relação às suas respectivas áreas de referência no que diz respeito especialmente aos parâmetros estruturais, florísticos e de processos ecológicos, e que o sucesso da restauração ainda não foi atingido. Entretanto, essas diferenças são maiores quando considerados os parâmetros de estrutura da vegetação. Isso indica que os processos ecológicos podem se restabelecer antes mesmo do desenvolvimento completo da complexidade estrutural da vegetação (como observada em florestas maduras).

No Capítulo 3, foram utilizados os mesmos dados sobre os processos ecológicos e os atributos funcionais apresentados no Capítulo 2, incluindo ainda a biomassa arbórea acima do solo. O objetivo foi identificar os diferentes parâmetros funcionais e de diversidade de espécies que influenciam os processos ecológicos em ecossistemas florestais. Os resultados indicaram que os principais preditores dos processos ecossistêmicos foram as variáveis relacionas aos atributos funcionais, seja na forma de composição funcional (CWM – atributo médio da comunidade ponderado pela abundância das espécies) ou como diversidade funcional. A riqueza de espécies teve apenas um papel secundário nos processos, indicando que são as características das plantas, e não o número de espécies existente, que realmente afeta o funcionamento do sistema. Além disso, os resultados obtidos indicam que dependendo do processo ecológico em questão, o efeito está relacionado à teoria de razão de massa (composição funcional) ou à teoria de complementariedade de nicho (diversidade funcional). Esses resultados são importantes para aplicação nas ações de restauração, uma vez que permitem identificar características de espécies desejáveis para modificar determinado atributo dos sistema, como, por exemplo, aumentar a produtividade primária ou a ciclagem de nutrientes no solo.

Por fim, o Capítulo 4 focou na aplicação de um modelo que tem como principal objetivo gerar uma comunidade funcionalmente mais similar ao ecossistema de referência. O modelo é baseado na composição de atributos funcionais do ecossistema de referência e nas espécies existentes na área de restauração. Dessa forma, é possível avaliar se a comunidade observada na área de restauração é similar àquela gerada pelo modelo e funcionalmente mais similar ao almejado na restauração. O modelo foi aplicado tanto para as espécies presentes no dossel, quando para aquelas do sub-bosque e os resultados indicaram que a comunidade restaurada é funcionalmente distinta da sua referência. Entretanto, a composição do sub-bosque (tanto observada, quanto predita) foi funcionalmente mais semelhante à referência do que a comunidade do dossel. Isso indica que as espécies que colonizaram os sítios de restauração após as intervenções de plantio são funcionalmente mais semelhantes ao ecossistema de referência do que as espécies que foram plantadas. A abordagem baseada em atributos funcionais permite monitorar a composição funcional de áreas em processo de restauração e avaliar trajetórias sucessionais, indicando necessidades de manejo.

O foco principal da tese foi o funcionamento dos ecossistemas florestais, direcionado a áreas em processo de restauração. Primeiro foi apresentada uma contextualização geral dos processos ecológicos em florestas, indicando as principais características que se modificam ao longo da sucessão, de modo a orientar o monitoramento das áreas em processo de restauração (Cap. 1); em seguida foram avaliadas diferenças na funcionalidade entre áreas em processo de restauração e florestas conservadas (Cap. 2), indicando as principais características das plantas que podem influenciar determinados processos ecológicos (Cap. 3) discutidos nos capítulos anteriores; para finalmente ser possível realizar previsões e propor ações para monitorar o funcionamento do ecossistema e as trajetórias sucessionais (Cap. 4). Os capítulos aqui apresentados estão interligados na medida que a informação de um complementa a interpretação do seguinte, da seguinte forma: compreender os processos ecológicos em ambientes florestais (Cap. 1) permite avaliar de forma mais adequada as diferenças na funcionalidade ecológica existentes em ambientes em restauração (Cap. 2); além disso, a identificação dos atributos funcionais que mais afetam um determinado processo ecológico de interesse (Cap. 3) podem ser utilizados tanto como indicadores para verificar mais facilmente a recuperação desses ecossistemas (Cap. 2), quanto na aplicação de modelos preditivos para potencializar o resultado de algum processo de interesse ou para monitorar trajetórias de sucessão (Cap. 4). A partir dos resultados desses modelos (Cap. 4), é possível sugerir ações de manejo em comunidades restauradas com o objetivo de aumentar a similaridade funcional com suas áreas de referência (Cap. 2), testando na prática de que forma a composição funcional afeta os processos ecológicos (Cap. 3).

Embora o presente trabalho abranja um grande número de processos ecológicos, não foi possível incluir alguns processos de grande importância em ambientes florestais. Os Capítulos 2 e 3 focaram principalmente em processos ecológicos relacionados a produtividade e ciclagem de nutrientes, sem incluir relações tróficas, dispersão de sementes, polinização, entre outros processos de extrema relevância para ambientes florestais. Entretanto, eles apresentam um abordagem conjunta com outros elementos do sistema (atributos estruturais e funcionais) que permitem uma avaliação integrada do ecossistema. Além disso, o Capítulo 2, que compara áreas de restauração com suas referências, apresenta apenas uma avaliação única no tempo, descrevendo a situação atual das áreas de restauração após cerca de 10 anos das intervenções de restauração. No futuro, é importante manter o monitoramento dos sítios de forma a avaliar modificações ao longo do tempo e se houve aumento da similaridade com relação às áreas de referência. Dessa forma, será possível propor ações de manejo com o objetivo de vencer barreiras que estejam limitando o desenvolvimento da vegetação. Por fim, as informações apresentadas nessa tese, além de serem utilizadas para o monitoramento de áreas de restauração, podem também servir para orientar o planejamento inicial desses projetos, sugerindo espécies adequadas para plantio, bem como suas respectivas abundâncias dependendo do objetivo desejado.

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ANEXO I

Tabela AI (S1.1). Lista de 106 estudos e 153 processos que entraram no critério de seleção e foram incluídos na nossa busca, bem como as informações extraídas de cada um deles. [Tabela referente ao Capítulo 1].

Table S1.1. List of the 106 studies and 153 processes that met the selection criteria and were included in our search, as well as the information extracted from each study.

ID	Authors	Year	Title	Journal	Climate	Country	Continent	Land use history	Restoration strategy
21	Andres Oria-de-Rueda, J., M. Hernandez-Rodriguez, P. Martin-Pinto, V. Pando and J. Olaizola	2010	Could artificial reforestations provide as much production and diversity of fungal species as natural forest stands in marginal Mediterranean areas?	Forest Ecology and Management 260(2): 171-180.	subtropical	Spain	Europe	agriculture/ pasture	active
22	Angelica Gomez-Ruiz, P., R. Lindig-Cisneros and O. Vargas-Rios	2013	Facilitation among plants: A strategy for the ecological restoration of the high-andean forest (Bogota, DC-Colombia).	Ecological Engineering 57: 267-275.	tropical	Colombia	South America	exotic species	active
25	Arevalo, J. R., J. D. Delgado and J. M. Fernandez-Palacios	2011	Regeneration of potential laurel forest under a native canopy and an exotic canopy, Tenerife (Canary Islands).	Forest Systems 20(2): 255-265.	subtropical	Spain	Europe	NA	active
40	Barnes, A. D. and H. M. Chapman	2014	Dispersal traits determine passive restoration trajectory of a Nigerian montane forest.	Acta Oecologica-International Journal of Ecology 56: 32-40.	tropical	Nigeria	Africa	agriculture/ pasture	passive
48	Bautista-Cruz, A., R. F. del Castillo, J. D. Etchevers-Barra, M. del Carmen Gutierrez-Castorena and A. Baez	2012	Selection and interpretation of soil quality indicators for forest recovery after clearing of a tropical montane cloud forest in Mexico.	Forest Ecology and Management 277: 74-80.	tropical	Mexico	North America	agriculture/ pasture	passive
60	Boerner, R. E. J., A. T. Coates, D. A. Yaussy and T. A. Waldrop	2008	Assessing ecosystem restoration alternatives in eastern deciduous forests: The view from belowground.	Restoration Ecology 16(3): 425-434.	temperate	United States	North America	fire suppression	active
61	Boothroyd-Roberts, K., D. Gagnon and B. Truax	2013	Can hybrid poplar plantations accelerate the restoration of forest understory attributes on abandoned fields?	Forest Ecology and Management 287: 77-89.	temperate	Canada	North America	agriculture/ pasture	active
61	Boothroyd-Roberts, K., D. Gagnon and B. Truax	2013	Can hybrid poplar plantations accelerate the restoration of forest understory attributes on abandoned fields?	Forest Ecology and Management 287: 77-89.	temperate	Canada	North America	agriculture/ pasture	active
61	Boothroyd-Roberts, K., D. Gagnon and B. Truax	2013	Can hybrid poplar plantations accelerate the restoration of forest understory attributes on abandoned fields?	Forest Ecology and Management 287: 77-89.	temperate	Canada	North America	agriculture/ pasture	active
61	Boothroyd-Roberts, K., D. Gagnon and B. Truax	2013	Can hybrid poplar plantations accelerate the restoration of forest understory attributes on abandoned fields?	Forest Ecology and Management 287: 77-89.	temperate	Canada	North America	agriculture/ pasture	active
62	Borders, B. D., J. C. Pushnik and D. M. Wood	2006	Comparison of leaf litter decomposition rates in restored and mature riparian forests on the Sacramento River, California.	Restoration Ecology 14(2): 308-315.	subtropical	United States	North America	agriculture/ pasture	active
76	Burgoyne, T. A. and T. H. DeLuca	2009	Short-term effects of forest restoration management on non-symbiotic nitrogen-fixation in western Montana.	Forest Ecology and Management 258(7): 1369-1375.	temperate	United States	North America	fire suppression	active
80	Campoe, O. C., C. Iannelli, J. L. Stape, R. L. Cook, J. C. T. Mendes and R. Vivian	2014	Atlantic forest tree species responses to silvicultural practices in a degraded pasture restoration plantation: From leaf physiology to survival and initial growth.	Forest Ecology and Management 313: 233-242.	tropical	Brazil	South America	NA	active
82	Carter, D. R., R. T. Fahey, K. Dreisilker, M. B. Bialecki and M. L. Bowles	2015	Assessing patterns of oak regeneration and C storage in relation to restoration-focused management, historical land use, and potential trade-offs.	Forest Ecology and Management 343: 53-62.	temperate	United States	North America	fire suppression	active
82	Carter, D. R., R. T. Fahey, K. Dreisilker, M. B. Bialecki and M. L. Bowles	2015	Assessing patterns of oak regeneration and C storage in relation to restoration-focused management, historical land use, and potential trade-offs.	Forest Ecology and Management 343: 53-62.	temperate	United States	North America	fire suppression	active
83	Castro, J., C. Puerta-Pinero, A. B. Leverkus, G. Moreno-Rueda and A. Sanchez-Miranda	2012	Post-fire salvage logging alters a key plant-animal interaction for forest regeneration.	Ecosphere 3(10).	subtropical	Spain	Europe	fire	active
83	Castro, J., C. Puerta-Pinero, A. B. Leverkus, G. Moreno-Rueda and A. Sanchez-Miranda	2012	Post-fire salvage logging alters a key plant-animal interaction for forest regeneration.	Ecosphere 3(10).	subtropical	Spain	Europe	fire	active
97	Cole, R. J., C. M. Litton, M. J. Koontz and R. K. Loh	2012	Vegetation Recovery 16 Years after Feral Pig Removal from a Wet Hawaiian Forest.	Biotropica 44(4): 463-471.	tropical	United States	North America	animal disturbance	passive
106	Correia, G. G. d. S. and S. V. Martins	2015	Banco de Sementes do Solo de Floresta Restaurada, Reserva Natural Vale, ES Santo State, Brazil.	Floresta e Ambiente 22(1): 79-87.	tropical	Brazil	South America	exotic species	active
117	Daronco, C., A. C. Galvao de Melo and G. Durigan	2013	Restored versus reference ecosystem: case study of plant community at a riparian forest in the Cerrado region, Assis, Sao Paulo State, Brazil.	Hoehnea 40(3): 485-498.	tropical	Brazil	South America	agriculture/ pasture	active

ID	Authors	Year	Title	Journal	Climate	Country	Continent	Land use history	Restoration strategy
120	de la Luz Avendano-Yanez, M., L. Rafael Sanchez-Velasquez, J. A. Meave and M. del Rosario Pineda-Lopez	2014	Is facilitation a promising strategy for cloud forest restoration?	Forest Ecology and Management 329: 328-333.	tropical	Mexico	North America	agriculture/ pasture	active
123	Descheemaeker, K., B. Muys, J. Nyssen, W. Sauwens, M. Haile, J. Poesen, D. Raes and J. Deckers	2009	Humus Form Development during Forest Restoration in Exclosures of the Tigray Highlands, Northern Ethiopia.	Restoration Ecology 17(2): 280-289.	tropical	Ethiopia	Africa	NA	active
123	Descheemaeker, K., B. Muys, J. Nyssen, W. Sauwens, M. Haile, J. Poesen, D. Raes and J. Deckers	2009	Humus Form Development during Forest Restoration in Exclosures of the Tigray Highlands, Northern Ethiopia.	Restoration Ecology 17(2): 280-289.	tropical	Ethiopia	Africa	NA	active
123	Descheemaeker, K., B. Muys, J. Nyssen, W. Sauwens, M. Haile, J. Poesen, D. Raes and J. Deckers	2009	Humus Form Development during Forest Restoration in Exclosures of the Tigray Highlands, Northern Ethiopia.	Restoration Ecology 17(2): 280-289.	tropical	Ethiopia	Africa	NA	active
133	Dodson, E. K. and D. W. Peterson	2010	Dry coniferous forest restoration and understory plant diversity: The importance of community heterogeneity and the scale of observation.	Forest Ecology and Management 260(10): 1702-1707.	temperate	United States	North America	fire suppression	active
135	Doi, R. and S. L. Ranamukhaarachchi	2013	Slow restoration of soil microbial functions in an Acacia plantation established on degraded land in Thailand.	International Journal of Environmental Science and Technology 10(4): 623-634.	tropical	Thailand	Asia	agriculture/ pasture	active
135	Doi, R. and S. L. Ranamukhaarachchi	2013	Slow restoration of soil microbial functions in an Acacia plantation established on degraded land in Thailand.	International Journal of Environmental Science and Technology 10(4): 623-634.	tropical	Thailand	Asia	agriculture/ pasture	active
137	Dominguez-Haydar, Y. and I. Armbrecht	2011	Response of Ants and Their Seed Removal in Rehabilitation Areas and Forests at El Cerrejon Coal Mine in Colombia.	Restoration Ecology 19: 178-184.	tropical	Colombia	South America	mining	active
138	Donato, D. C., J. B. Fontaine, J. L. Campbell, W. D. Robinson, J. B. Kauffman and B. E. Law	2006	Post-wildfire logging hinders regeneration and increases fire risk.	Science 311(5759): 352-352.	temperate	United States	North America	NA	active
141	Dou, X., Q. Deng, M. Li, W. Wang, Q. Zhang and X. Cheng	2013	Reforestation of Pinus massoniana alters soil organic carbon and nitrogen dynamics in eroded soil in south China.	Ecological Engineering 52: 154-160.	subtropical	China	Asia	agriculture/ pasture	active
141	Dou, X., Q. Deng, M. Li, W. Wang, Q. Zhang and X. Cheng	2013	Reforestation of Pinus massoniana alters soil organic carbon and nitrogen dynamics in eroded soil in south China.	Ecological Engineering 52: 154-160.	subtropical	China	Asia	agriculture/ pasture	active
150	Dwyer, J. M., R. Fensham and Y. M. Buckley	2010	Restoration thinning accelerates structural development and carbon sequestration in an endangered Australian ecosystem.	Journal of Applied Ecology 47(3): 681-691.	subtropical	Australia	Oceania	NA	active
155	Elliott, K. J., J. M. Vose, J. D. Knoepp and B. D. Clinton	2012	Restoration of shortleaf pine (Pinus echinata)-hardwood ecosystems severely impacted by the southern pine beetle (Dendroctonus frontalis).	Forest Ecology and Management 274: 181-200.	temperate	United States	North America	NA	active
155	Elliott, K. J., J. M. Vose, J. D. Knoepp and B. D. Clinton	2012	Restoration of shortleaf pine (Pinus echinata)-hardwood ecosystems severely impacted by the southern pine beetle (Dendroctonus frontalis).	Forest Ecology and Management 274: 181-200.	temperate	United States	North America	NA	active
155	Elliott, K. J., J. M. Vose, J. D. Knoepp and B. D. Clinton	2012	Restoration of shortleaf pine (Pinus echinata)-hardwood ecosystems severely impacted by the southern pine beetle (Dendroctonus frontalis).	Forest Ecology and Management 274: 181-200.	temperate	United States	North America	NA	active
155	Elliott, K. J., J. M. Vose, J. D. Knoepp and B. D. Clinton	2012	Restoration of shortleaf pine (Pinus echinata)-hardwood ecosystems severely impacted by the southern pine beetle (Dendroctonus frontalis).	Forest Ecology and Management 274: 181-200.	temperate	United States	North America	NA	active
161	Fajardo, L., G. Cuenca, P. Arrindell, R. Capote and Z. Hasmy	2011	USE OF ARBUSCULAR MYCORRHIZAL FUNGI IN ECOLOGICAL RESTORATION.	Interciencia 36(12): 931-936.	tropical	Venezuela	South America	mining	active
162	Falcao, J. C. F., W. Dattilo and T. J. Izzo	2015	Efficiency of different planted forests in recovering biodiversity and ecological interactions in Brazilian Amazon.	Forest Ecology and Management 339: 105-111.	tropical	Brazil	South America	agriculture/ pasture	active

ID	Authors	Year	Title	Journal	Climate	Country	Continent	Land use history	Restoration strategy
168	Ferreira Bertacchi, M. I., P. H. Santin Brancalion, G. Brondani, J. C. Medeiros and R. R. Rodrigues	2012	CHARACTERIZATION OF THE MICRO-SITE CONDITIONS FROM RESTORED AREAS WITH DIFFERENT AGES.	Revista Arvore 36(5): 895-905.	tropical	Brazil	South America	NA	active
168	Ferreira Bertacchi, M. I., P. H. Santin Brancalion, G. Brondani, J. C. Medeiros and R. R. Rodrigues	2012	CHARACTERIZATION OF THE MICRO-SITE CONDITIONS FROM RESTORED AREAS WITH DIFFERENT AGES.	Revista Arvore 36(5): 895-905.	tropical	Brazil	South America	NA	active
168	Ferreira Bertacchi, M. I., P. H. Santin Brancalion, G. Brondani, J. C. Medeiros and R. R. Rodrigues	2012	CHARACTERIZATION OF THE MICRO-SITE CONDITIONS FROM RESTORED AREAS WITH DIFFERENT AGES.	Revista Arvore 36(5): 895-905.	tropical	Brazil	South America	NA	active
168	Ferreira Bertacchi, M. I., P. H. Santin Brancalion, G. Brondani, J. C. Medeiros and R. R. Rodrigues	2012	CHARACTERIZATION OF THE MICRO-SITE CONDITIONS FROM RESTORED AREAS WITH DIFFERENT AGES.	Revista Arvore 36(5): 895-905.	tropical	Brazil	South America	NA	active
175	Forbes, A. R. and J. L. Craig	2013	Assessing the role of revegetation in achieving restoration goals on Tiritiri Matangi Island.	New Zealand Journal of Ecology 37(3): 343-352.	subtropical	New Zealand	Oceania	agriculture/ pasture	active
178	Frick, K. M., A. L. Ritchie and S. L. Krauss	2014	Field of Dreams: Restitution of Pollinator Services in Restored Bird-Pollinated Plant Populations.	Restoration Ecology 22(6): 832-840.	subtropical	Australia	Oceania	mining	active
187	Garcia, L. C., M. V. Cianciaruso, D. B. Ribeiro, F. A. Maes dos Santos and R. R. Rodrigues	2015	Flower functional trait responses to restoration time.	Applied Vegetation Science 18(3): 402-412.	tropical	Brazil	South America	agriculture/ pasture	active
188	Garcia-Robledo, C.	2010	Restoration of Plant-Pollinator Interactions: Pollination Neighborhood and Asymmetric Pollen Flow Between Restored Habitats in a Beetle-Pollinated Aroid.	Restoration Ecology 18: 94-102.	tropical	Colombia	South America	agriculture/ pasture	passive
193	Giai, C. and R. E. J. Boerner	2007	Effects of ecological restoration on microbial activity, microbial functional diversity, and soil organic matter in mixed-oak forests of southern Ohio, USA.	Applied Soil Ecology 35(2): 281-290.	temperate	United States	North America	fire suppression	active
193	Giai, C. and R. E. J. Boerner	2007	Effects of ecological restoration on microbial activity, microbial functional diversity, and soil organic matter in mixed-oak forests of southern Ohio, USA.	Applied Soil Ecology 35(2): 281-290.	temperate	United States	North America	fire suppression	active
196	Gibb, H.	2012	Effects of planting method on the recovery of arboreal ant activity on revegetated farmland.	Austral Ecology 37(7): 789-799.	temperate	Australia	Oceania	agriculture/ pasture	active
197	Gibb, H. and S. A. Cunningham	2009	Does the availability of arboreal honeydew determine the prevalence of ecologically dominant ants in restored habitats?	Insectes Sociaux 56(4): 405-412.	temperate	Australia	Oceania	agriculture/ pasture	active
207	Gong, X., Y. Liu, Q. Li, X. Wei, X. Guo, D. Niu, W. Zhang, J. Zhang and L. Zhang	2013	Sub-tropic degraded red soil restoration: Is soil organic carbon build-up limited by nutrients supply.	Forest Ecology and Management 300: 77-87.	subtropical	China	Asia	agriculture/ pasture	active
218	Gundale, M. J., T. H. DeLuca, C. E. Fiedler, P. W. Ramsey, M. G. Harrington and J. E. Gannon	2005	Restoration treatments in a Montana ponderosa pine forest: Effects on soil physical, chemical and biological properties.	Forest Ecology and Management 213(1-3): 25-38.	temperate	United States	North America	fire suppression	active
237	Heleno, R., I. Lacerda, J. A. Ramos and J. Memmott	2010	Evaluation of restoration effectiveness: community response to the removal of alien plants.	Ecological Applications 20(5): 1191-1203.	temperate	Portugal	Europe	agriculture/ pasture	active
240	Hernandez, Y., K. Boege, R. Lindig-Cisneros and E. del-Val	2014	LEPIDOPTERAN HERBIVORY IN RESTORED AND SUCCESSIONAL SITES IN A TROPICAL DRY FOREST.	Southwestern Naturalist 59(1): 66-74.	tropical	Mexico	North America	agriculture/ pasture	active
245	Holl, K. D. and E. E. Crone	2004	Applicability of landscape and island biogeography theory to restoration of riparian understorey plants.	Journal of Applied Ecology 41(5): 922-933.	subtropical	United States	North America	agriculture/ pasture	active
250	Hubbard, R. M., J. M. Vose, B. D. Clinton, K. J. Elliott and J. D. Knoepp	2004	Stand restoration burning in oak-pine forests in the southern Appalachians: effects on aboveground biomass and carbon and nitrogen cycling.	Forest Ecology and Management 190(2-3): 311-321.	temperate	United States	North America	fire suppression	active
250	Hubbard, R. M., J. M. Vose, B. D. Clinton, K. J. Elliott and J. D. Knoepp	2004	Stand restoration burning in oak-pine forests in the southern Appalachians: effects on aboveground biomass and carbon and nitrogen cycling.	Forest Ecology and Management 190(2-3): 311-321.	temperate	United States	North America	fire suppression	active
250	Hubbard, R. M., J. M. Vose, B. D. Clinton, K. J. Elliott and J. D. Knoepp	2004	Stand restoration burning in oak-pine forests in the southern Appalachians: effects on aboveground biomass and carbon and nitrogen cycling.	Forest Ecology and Management 190(2-3): 311-321.	temperate	United States	North America	fire suppression	active

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260	Jiao, J., Z. Zhang, W. Bai, Y. Jia and N. Wang	2012	Assessing the Ecological Success of Restoration by Afforestation on the Chinese Loess Plateau.	Restoration Ecology 20(2): 240-249.	temperate	China	Asia	agriculture/ pasture	active
260	Jiao, J., Z. Zhang, W. Bai, Y. Jia and N. Wang	2012	Assessing the Ecological Success of Restoration by Afforestation on the Chinese Loess Plateau.	Restoration Ecology 20(2): 240-249.	temperate	China	Asia	agriculture/ pasture	active
266	Kaiser, C. N., D. M. Hansen and C. B. Mueller	2008	Habitat structure affects reproductive success of the rare endemic tree Syzygium mamillatum (Myrtaceae) in restored and unrestored sites in mauritius.	Biotropica 40(1): 86-94.	tropical	Mauritius	Africa	exotic species	active
273	Kaye, J. P. and S. C. Hart	1998	Ecological restoration alters nitrogen transformations in a ponderosa pine bunchgrass ecosystem.	Ecological Applications 8(4): 1052-1060.	subtropical	United States	North America	fire suppression	active
274	Kaye, J. P., S. C. Hart, R. C. Cobb and J. E. Stone	1999	Water and nutrient outflow following the ecological restoration of a ponderosa pine-bunchgrass ecosystem.	Restoration Ecology 7(3): 252-261.	subtropical	United States	North America	fire suppression	active
274	Kaye, J. P., S. C. Hart, R. C. Cobb and J. E. Stone	1999	Water and nutrient outflow following the ecological restoration of a ponderosa pine-bunchgrass ecosystem.	Restoration Ecology 7(3): 252-261.	subtropical	United States	North America	fire suppression	active
275	Kaye, J. P., S. C. Hart, P. Z. Fule, W. W. Covington, M. M. Moore and M. W. Kaye	2005	Initial carbon, nitrogen, and phosphorus fluxes following ponderosa pine restoration treatments.	Ecological Applications 15(5): 1581-1593.	subtropical	United States	North America	fire suppression	active
275	Kaye, J. P., S. C. Hart, P. Z. Fule, W. W. Covington, M. M. Moore and M. W. Kaye	2005	Initial carbon, nitrogen, and phosphorus fluxes following ponderosa pine restoration treatments.	Ecological Applications 15(5): 1581-1593.	subtropical	United States	North America	fire suppression	active
287	Korb, J. E., N. C. Johnson and W. W. Covington	2003	Arbuscular mycorrhizal propagule densities respond rapidly to ponderosa pine restoration treatments.	Journal of Applied Ecology 40(1): 101-110.	subtropical	United States	North America	fire suppression	active
317	Lindell, C. A. and G. M. Thurston	2013	Bird Pollinator Visitation is Equivalent in Island and Plantation Planting Designs in Tropical Forest Restoration Sites.	Sustainability 5(3): 1177-1187.	tropical	Costa Rica	Central America	NA	active
322	Liu, Y., J.-S. Chen, Q. Liu and Y. Wu	2006	Nitrification and denitrification in subalpine coniferous forests of different restoration stages in western Sichuan, China.	Zhiwu Shengtai Xuebao 30(1): 90-96.	subtropical	China	Asia	logging	passive
322	Liu, Y., J.-S. Chen, Q. Liu and Y. Wu	2006	Nitrification and denitrification in subalpine coniferous forests of different restoration stages in western Sichuan, China.	Zhiwu Shengtai Xuebao 30(1): 90-96.	subtropical	China	Asia	logging	passive
323	Liu, Y., X. Wei, X. Guo, D. Niu, J. Zhang, X. Gong and Y. Jiang	2012	The long-term effects of reforestation on soil microbial biomass carbon in sub-tropic severe red soil degradation areas.	Forest Ecology and Management 285: 77-84.	subtropical	China	Asia	NA	active
325	Lloyd, R. A., K. A. Lohse and T. P. A. Ferre	2013	Influence of road reclamation techniques on forest ecosystem recovery.	Frontiers in Ecology and the Environment 11(2): 75-81.	temperate	United States	North America	road	passive
327	Lomov, B., D. A. Keith and D. F. Hochuli	2009	Linking ecological function to species composition in ecological restoration: Seed removal by ants in recreated woodland.	Austral Ecology 34(7): 751-760.	subtropical	Australia	Oceania	agriculture/ pasture	active
328	Lomov, B., D. A. Keith and D. F. Hochuli	2010	Pollination and plant reproductive success in restored urban landscapes dominated by a pervasive exotic pollinator.	Landscape and Urban Planning 96(4): 232-239.	subtropical	Australia	Oceania	agriculture/ pasture	active
338	Martin, K. L., M. D. Hurteau, B. A. Hungate, G. W. Koch and M. P. North	2015	Carbon Tradeoffs of Restoration and Provision of Endangered Species Habitat in a Fire-Maintained Forest.	Ecosystems 18(1): 76-88.	subtropical	United States	North America	fire suppression	active
344	Mateus, F. A., C. d. C. Miranda, R. Valcarcel and P. H. A. Figueiredo	2013	Estoque e capacidade de retenção hídrica da serrapilheira acumulada na restauração florestal de áreas perturbadas na Mata Atlântica restoration of disturbed areas in the Atlantic Rainforest.	Floresta e Ambiente(ahead): 0-0.	tropical	Brazil	South America	agriculture/ pasture	passive
363	Morrison, E. B., C. A. Lindell, K. D. Holl and R. A. Zahawi	2010	Patch size effects on avian foraging behaviour: implications for tropical forest restoration design.	Journal of Applied Ecology 47(1): 130-138.	tropical	Costa Rica	Central America	agriculture/ pasture	active
365	Mota, M. C. and J. M. Domingues Torezan	2013	Necromass in 4, 6 and 8-year old Atlantic Forest restoration sites.	Hoehnea 40(3): 499-505.	tropical	Brazil	South America	agriculture/ pasture	active
368	Munro, N. T., J. Fischer, J. Wood and D. B. Lindenmayer	2012	Assessing ecosystem function of restoration plantings in south-eastern Australia.	Forest Ecology and Management 282: 36-45.	subtropical	Australia	Oceania	agriculture/ pasture	active
368	Munro, N. T., J. Fischer, J. Wood and D. B. Lindenmayer	2012	Assessing ecosystem function of restoration plantings in south-eastern Australia.	Forest Ecology and Management 282: 36-45.	subtropical	Australia	Oceania	agriculture/ pasture	active

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379	Ngugi, M. R., R. W. Johnson and W. J. F. McDonald	2011	Restoration of ecosystems for biodiversity and carbon sequestration: Simulating growth dynamics of brigalow vegetation communities in Australia.	Ecological Modelling 222(3): 785-794.	subtropical	Australia	Oceania	agriculture/ pasture	passive
379	Ngugi, M. R., R. W. Johnson and W. J. F. McDonald	2011	Restoration of ecosystems for biodiversity and carbon sequestration: Simulating growth dynamics of brigalow vegetation communities in Australia.	Ecological Modelling 222(3): 785-794.	subtropical	Australia	Oceania	agriculture/ pasture	passive
382	Nichols, P. W. B., E. C. Morris and D. A. Keith	2010	Testing a facilitation model for ecosystem restoration: Does tree planting restore ground layer species in a grassy woodland?	Austral Ecology 35(8): 888-897.	subtropical	Australia	Oceania	agriculture/ pasture	active
389	Onaindia, M., I. Ametzaga-Arregi, M. San Sebastian, A. Mitxelena, G. Rodriguez-Loinaz, L. Pena and J. G. Alday	2013	Can understorey native woodland plant species regenerate under exotic pine plantations using natural succession?	Forest Ecology and Management 308: 136-144.	temperate	Spain	Europe	NA	active
400	Parrotta, J. A. and O. H. Knowles	2001	Restoring tropical forests on lands mined for bauxite: Examples from the Brazilian Amazon.	Ecological Engineering 17(2-3): 219-239.	tropical	Brazil	South America	mining	active
402	Perkins, K. S., J. R. Nimmo and A. C. Medeiros	2012	Effects of native forest restoration on soil hydraulic properties, Auwahi, Maui, Hawaiian Islands.	Geophysical Research Letters 39.	tropical	Hawaii	North America	agriculture/ pasture	active
403	Perring, M. P., J. Jonson, D. Freudenberger, R. Campbell, M. Rooney, R. J. Hobbs and R. J. Standish	2015	Soil-vegetation type, stem density and species richness influence biomass of restored woodland in south-western Australia.	Forest Ecology and Management 344: 53-62.	subtropical	Australia	Oceania	agriculture/ pasture	active
410	Podrazsky, V., A. Kapicka and M. Kouba	2010	RESTORATION OF FOREST SOILS AFTER BULLDOZER SITE PREPARATION IN THE ORE MOUNTAINS OVER 20 YEARS DEVELOPMENT.	Ekologia (Bratislava) 29(3): 281-289.	temperate	Czech Republic	Europe	NA	active
420	Proenca, V., H. M. Pereira and L. Vicente	2010	Resistance to wildfire and early regeneration in natural broadleaved forest and pine plantation.	Acta Oecologica-International Journal of Ecology 36(6): 626-633.	temperate	Portugal	Europe	fire	passive
425	Rahe, N. H., K. W. J. Williard and J. E. Schoonover	2015	Restoration of Riparian Buffer Function in Reclaimed Surface Mine Soils.	Journal of the American Water Resources Association 51(4): 898-909.	subtropical	United States	North America	mining	active
425	Rahe, N. H., K. W. J. Williard and J. E. Schoonover	2015	Restoration of Riparian Buffer Function in Reclaimed Surface Mine Soils.	Journal of the American Water Resources Association 51(4): 898-909.	subtropical	United States	North America	mining	active
430	Reay, S. D. and D. A. Norton	1999	Assessing the success of restoration plantings in a temperate New Zealand forest.	Restoration Ecology 7(3): 298-308.	temperate	New Zealand	Oceania	NA	active
435	Ren, H., Z. Li, W. Shen, Z. Yu, S. Peng, C. Liao, M. Ding and J. Wu	2007	Changes in biodiversity and ecosystem function during the restoration of a tropical forest in south China.	Science in China Series C-Life Sciences 50(2): 277-284.	subtropical	China	Asia	logging	active
435	Ren, H., Z. Li, W. Shen, Z. Yu, S. Peng, C. Liao, M. Ding and J. Wu	2007	Changes in biodiversity and ecosystem function during the restoration of a tropical forest in south China.	Science in China Series C-Life Sciences 50(2): 277-284.	subtropical	China	Asia	logging	active
454	Rowland, S. M., C. E. Prescott, S. J. Grayston, S. A. Quideau and G. E. Bradfield	2009	Recreating a Functioning Forest Soil in Reclaimed Oil Sands in Northern Alberta: An Approach for Measuring Success in Ecological Restoration.	Journal of Environmental Quality 38(4): 1580-1590.	boreal	Canada	North America	mining	active
454	Rowland, S. M., C. E. Prescott, S. J. Grayston, S. A. Quideau and G. E. Bradfield	2009	Recreating a Functioning Forest Soil in Reclaimed Oil Sands in Northern Alberta: An Approach for Measuring Success in Ecological Restoration.	Journal of Environmental Quality 38(4): 1580-1590.	boreal	Canada	North America	mining	active
456	Ruiz-Jaen, M. C. and T. M. Aide	2005	Vegetation structure, species diversity, and ecosystem processes as measures of restoration success.	Forest Ecology and Management 218(1-3): 159-173.	subtropical	Puerto Rico	Central America	logging	active
456	Ruiz-Jaen, M. C. and T. M. Aide	2005	Vegetation structure, species diversity, and ecosystem processes as measures of restoration success.	Forest Ecology and Management 218(1-3): 159-173.	subtropical	Puerto Rico	Central America	logging	active

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457	Ruiz-Jaen, M. C. and T. M. Aide	2006	An integrated approach for measuring urban forest restoration success.	Urban Forestry & Urban Greening 4(2): 55-68.	subtropical	Puerto Rico	Central America	exotic species	active
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470	Schwenke, G. D., L. Ayre, D. R. Mulligan and L. C. Bell	2000	Soil stripping and replacement for the rehabilitation of bauxite-mined land at Weipa. II. Soil organic matter dynamics in mine soil chronosequences.	Australian Journal of Soil Research 38(2): 371-393.	tropical	Australia	Oceania	mining	active
471	Selmants, P. C., S. C. Hart, S. I. Boyle, C. A. Gehring and B. A. Hungate	2008	Restoration of a ponderosa pine forest increases soil CO(2) efflux more than either water or nitrogen additions.	Journal of Applied Ecology 45(3): 913-920.	subtropical	United States	North America	fire suppression	active
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479	Sitters, J., M. Holmgren, J. J. Stoorvogel and B. C. Lopez	2012	Rainfall-Tuned Management Facilitates Dry Forest Recovery.	Restoration Ecology 20(1): 33-42.	tropical	Peru	South America	NA	active
479	Sitters, J., M. Holmgren, J. J. Stoorvogel and B. C. Lopez	2012	Rainfall-Tuned Management Facilitates Dry Forest Recovery.	Restoration Ecology 20(1): 33-42.	tropical	Peru	South America	NA	active
481	Smith, J. E., D. McKay, G. Brenner, J. McIver and J. W. Spatafora	2005	Early impacts of forest restoration treatments on the ectomycorrhizal fungal community and fine root biomass in a mixed conifer forest.	Journal of Applied Ecology 42(3): 526-535.	temperate	United States	North America	fire suppression	active
481	Smith, J. E., D. McKay, G. Brenner, J. McIver and J. W. Spatafora	2005	Early impacts of forest restoration treatments on the ectomycorrhizal fungal community and fine root biomass in a mixed conifer forest.	Journal of Applied Ecology 42(3): 526-535.	temperate	United States	North America	fire suppression	active
499	Suganuma, M. S., G. B. de Assis and G. Durigan	2014	Changes in plant species composition and functional traits along the successional trajectory of a restored patch of Atlantic Forest.	Community Ecology 15(1): 27-36.	tropical	Brazil	South America	agriculture/ pasture	active
501	Suganuma, M. S. and J. M. Domingues Torezan	2013	Evolution of ecosystem processes in Semideciduous Atlantic Forest restoration sites.	Hoehnea 40(3): 557-565.	tropical	Brazil	South America	NA	active
501	Suganuma, M. S. and J. M. Domingues Torezan	2013	Evolution of ecosystem processes in Semideciduous Atlantic Forest restoration sites.	Hoehnea 40(3): 557-565.	tropical	Brazil	South America	NA	active
501	Suganuma, M. S. and J. M. Domingues Torezan	2013	Evolution of ecosystem processes in Semideciduous Atlantic Forest restoration sites.	Hoehnea 40(3): 557-565.	tropical	Brazil	South America	NA	active
502	Suganuma, M. S. and G. Durigan	2015	Indicators of restoration success in riparian tropical forests using multiple reference ecosystems.	Restoration Ecology 23(3): 238-251.	tropical	Brazil	South America	agriculture/ pasture	active
503	Sun, Z., H. Ren, V. Schaefer, Q. Guo and J. Wang	2014	Using ecological memory as an indicator to monitor the ecological restoration of four forest plantations in subtropical China.	Environmental Monitoring and Assessment 186(12): 8229-8247.	subtropical	China	Asia	NA	active
503	Sun, Z., H. Ren, V. Schaefer, Q. Guo and J. Wang	2014	Using ecological memory as an indicator to monitor the ecological restoration of four forest plantations in subtropical China.	Environmental Monitoring and Assessment 186(12): 8229-8247.	subtropical	China	Asia	NA	active
504	Suzuki, M. and E. Ito	2014	Combined effects of gap creation and deer exclusion on restoration of belowground systems of secondary woodlands: A field experiment in warm-temperate monsoon Asia.	Forest Ecology and Management 329: 227-236.	temperate	Japan	Asia	animal disturbance	active

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524	Vacchiano, G., S. Stanchi, G. Marinari, D. Ascoli, E. Zanini and R. Motta	2014	Fire severity, residuals and soil legacies affect regeneration of Scots pine in the Southern Alps.	Science of the Total Environment 472: 778-788.	temperate	Italy	Europe	fire	passive
528	Vallauri, D. R., J. Aronson and M. Barbero	2002	An analysis of forest restoration 120 years after reforestation on badlands in the Southwestern Alps.	Restoration Ecology 10(1): 16-26.	temperate	France	Europe	NA	active
528	Vallauri, D. R., J. Aronson and M. Barbero	2002	An analysis of forest restoration 120 years after reforestation on badlands in the Southwestern Alps.	Restoration Ecology 10(1): 16-26.	temperate	France	Europe	NA	active
533	Vasconcellos, R. L. F., T. D. Zucchi, R. G. Taketani, F. D. Andreote and E. J. B. N. Cardoso	2014	Bacterial community characterization in the soils of native and restored rainforest fragments.	International Journal of General and Molecular Microbiology 106(5): 947-957.	tropical	Brazil	South America	NA	active
533	Vasconcellos, R. L. F., T. D. Zucchi, R. G. Taketani, F. D. Andreote and E. J. B. N. Cardoso	2014	Bacterial community characterization in the soils of native and restored rainforest fragments.	International Journal of General and Molecular Microbiology 106(5): 947-957.	tropical	Brazil	South America	NA	active
537	Vlachodimos, K., E. M. Papatheodorou, J. Diamantopoulos and N. Monokrousos	2013	Assessment of Robinia pseudoacacia cultivations as a restoration strategy for reclaimed mine spoil heaps.	Environmental Monitoring and Assessment 185(8): 6921-6932.	subtropical	Macedonia	Europe	mining	active
543	Wang, Y., Z. Ouyang, H. Zheng, X. Wang, F. Chen and J. Zeng	2011	Carbon metabolism of soil microbial communities of restored forests in Southern China.	Journal of Soils and Sediments 11(5): 789-799.	subtropical	China	Asia	NA	active
543	Wang, Y., Z. Ouyang, H. Zheng, X. Wang, F. Chen and J. Zeng	2011	Carbon metabolism of soil microbial communities of restored forests in Southern China.	Journal of Soils and Sediments 11(5): 789-799.	subtropical	China	Asia	NA	active
544	Wang, Z., C. Daun, L. Yuan, J. Rao, Z. Zhou, J. Li, C. Yang and W. Xu	2010	Assessment of the restoration of a degraded semi-humid evergreen broadleaf forest ecosystem by combined single-indicator and comprehensive model method.	Ecological Engineering 36(6): 757-767.	subtropical	China	Asia	agriculture/ pasture	active
548	Ward, S. C.	2000	Soil development on rehabilitated bauxite mines in south-west Australia.	Australian Journal of Soil Research 38(2): 453-464.	subtropical	Australia	Oceania	mining	active
551	Wei, X., Q. Li, Y. Liu, S. Liu, X. Guo, L. Zhang, D. Niu and W. Zhang	2013	Restoring ecosystem carbon sequestration through afforestation: A sub-tropic restoration case study.	Forest Ecology and Management 300: 60-67.	subtropical	China	Asia	agriculture/ pasture	active
560	Williams, N. M.	2011	Restoration of Nontarget Species: Bee Communities and Pollination Function in Riparian Forests.	Restoration Ecology 19(4): 450-459.	subtropical	United States	North America	agriculture/ pasture	active
584	Zanini, L. and G. Ganade	2005	Restoration of Araucaria forest: The role of perches, pioneer vegetation, and soil fertility.	Restoration Ecology 13(3): 507-514.	subtropical	Brazil	South America	exotic species	active
585	Zanne, A. E. and C. A. Chapman	2001	Expediting reforestation in tropical grasslands: Distance and isolation from seed sources in plantations.	Ecological Applications 11(6): 1610-1621.	tropical	Uganda	Africa	logging	active
592	Zheng, H., Z. Y. Ouyang, X. K. Wang, Z. G. Fang, T. Q. Zhao and H. Miao	2005	Effects of regenerating forest cover on soil microbial communities: A case study in hilly red soil region, Southern China.	Forest Ecology and Management 217(2-3): 244-254.	subtropical	China	Asia	logging	active
598	Zou, L.-Q., F.-S. Chen, D. S. Duncan, X.-M. Fang and H. Wang	2015	Reforestation and slope-position effects on nitrogen, phosphorus pools, and carbon stability of various soil aggregates in a red soil hilly land of subtropical China.	Canadian Journal of Forest Research 45(1): 26-35.	subtropical	China	Asia	logging	active
003a	Avera, B. N., Strahm, B. D., Burger, J. A., & Zipper, C. E.	2015	Development of ecosystem structure and function on reforested surface-mined lands in the Central Appalachian Coal Basin of the United States	New Forests, 46(5-6), 683-702	temperate	United States	North America	mining	active

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019a	da Silva, F. R., Montoya, D., Furtado, R., Memmott, J., Pizo, M. A., & Rodrigues, R. R.	2015	The restoration of tropical seed dispersal networks	Restoration Ecology, 23(6), 852-860	tropical	Brazil	South America	NA	active
028a	Ferez, A. P. C., Campoe, O. C., Mendes, J. C. T., & Stape, J. L.	2015	Silvicultural opportunities for increasing carbon stock in restoration of Atlantic forests in Brazil	Forest Ecology and Management, 350, 40-45	tropical	Brazil	South America	agriculture/ pasture	active
028a	Ferez, A. P. C., Campoe, O. C., Mendes, J. C. T., & Stape, J. L.	2015	Silvicultural opportunities for increasing carbon stock in restoration of Atlantic forests in Brazil	Forest Ecology and Management, 350, 40-45	tropical	Brazil	South America	agriculture/ pasture	active
044a	Jacobs, B. F.	2015	Restoration of degraded transitional (pinon-juniper) woodland sites improves ecohydrologic condition and primes understory resilience to subsequent disturbance	Ecohydrology, 8(8), 1417-1428	subtropical	United States	North America	NA	active
052a	MacFarlane, D. W., Kinzer, A. T., & Banks, J. E.	2015	Coupled human-natural regeneration of indigenous coastal dry forest in Kenya	Forest Ecology and Management, 354, 149-159	tropical	Kenya	Africa	logging	active
060a	Ngugi, M. R., Neldner, V. J., Doley, D., Kusy, B., Moore, D., & Richter, C.	2015	Soil moisture dynamics and restoration of self-sustaining native vegetation ecosystem on an open-cut coal mine	Restoration Ecology, 23(5), 615-624	subtropical	Australia	Oceania	mining	active
066a	Podadera, D. S., Engel, V. L., Parrotta, J. A., Machado, D. L., Sato, L. M., & Durigan, G.	2015	Influence of Removal of a Non-native Tree Species Mimosa caesalpiniifolia Benth. on the Regenerating Plant Communities in a Tropical Semideciduous Forest Under Restoration in Brazil	Environmental Management, 56(5), 1148-1158	subtropical	Brazil	South America	exotic species	active
084a	Strahan, R. T., Stoddard, M. T., Springer, J. D., & Huffman, D. W.	2015	Increasing weight of evidence that thinning and burning treatments help restore understory plant communities in ponderosa pine forests	Forest Ecology and Management, 353, 208-220	subtropical	United States	North America	fire suppression	active
092a	Wiechmann, M. L., Hurteau, M. D., North, M. P., Koch, G. W., & Jerabkova, L.	2015	The carbon balance of reducing wildfire risk and restoring process: an analysis of 10-year post-treatment carbon dynamics in a mixed-conifer forest	Climatic Change, 132(4), 709-719	subtropical	United States	North America	fire suppression	active
103a	Bertacchi, M. I. F., Amazonas, N. T., Brancalion, P. H. S., Brondani, G. E., de Oliveira, A. C. S., de Pascoa, M. A. R., & Rodrigues, R. R.	2016	Establishment of tree seedlings in the understory of restoration plantations: natural regeneration and enrichment plantings	Restoration Ecology, 24(1), 100-108	tropical	Brazil	South America	agriculture/ pasture	active
106a	Campos, W. H., & Martins, S. V.	2016	NATURAL REGENERATION STRATUM AS AN INDICATOR OF RESTORATION IN AREA OF ENVIRONMENTAL COMPENSATION FOR MINING LIMESTONE, MUNICIPALITY OF BARROSO, MG, BRAZIL	Revista Arvore, 40(2), 189-196	tropical	Brazil	South America	mining	active
125a	Londe, V., De Sousa, H. C., & Kozovits, A. R.	2016	Litterfall as an indicator of productivity and recovery of ecological functions in a rehabilitated riparian forest at Das Velhas River, southeast Brazil	Tropical Ecology, 57(2), 355-360	tropical	Brazil	South America	NA	active
138a	Smith, C. M. S., Bowie, M. H., Hahner, J. L., Boyer, S., Kim, Y. N., Zhong, H. T., . . . Dickinson, N.	2016	Punakaiki Coastal Restoration Project: A case study for a consultative and multidisciplinary approach in selecting indicators of restoration success for a sand mining closure site, West Coast, New Zealand	Catena, 136, 91-103	temperate	New Zealand	Oceania	mining	active

(continuação Tabela AI)

ID	Restoration action	Restoration age (yrs)	Maximum time (yrs)	Frequency of measurement	Frequency: space or time	Reference	Number of functions	Function category	Ecological process	Variable measured	Result category
21	planting	45-55	(3) 15+	single	NA	yes	single function	nutrient cycling	soil biotic processes	fungi diversity	(1) similar to reference
22	weeding	<1	(1) up to 5	single	NA	yes	single function	trophic interactions	facilitation	plant survival/growth	(2) positive
25	planting	60+	(3) 15+	single	NA	yes	single function	recruitment	seedling	seedling density/richness	(1) similar to reference
40	fencing	5	(1) up to 5	single	NA	no	single function	recruitment	both seed and seedling	seed and seedling density/richness	(5) unclear
48	none	15, 45, 75	(3) 15+	multiple	space	yes	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
60	thinning/burning	4	(1) up to 5	multiple	time	no	single function	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial activity/diversity	(5) unclear
61	planting	10	(2) 5 to 15	single	NA	yes	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(1) similar to reference
61	planting	10	(2) 5 to 15	single	NA	yes	function_2	productivity	biomass rates	litter stock	(1) similar to reference
61	planting	10	(2) 5 to 15	single	NA	yes	function_3	recruitment	seedling	seedling density/richness	(2) positive
61	planting	10	(2) 5 to 15	single	NA	yes	function_4	water relations	soil moisture	soil moisture	(4) negative
62	planting	4, 7, 9	(2) 5 to 15	multiple	space	yes	single function	nutrient cycling	soil biotic processes	decomposition	(1) similar to reference
76	thinning/burning	4	(1) up to 5	single	NA	no	single function	nutrient cycling	soil biotic processes	microbial community	(3) no effect
80	planting	2.5	(1) up to 5	single	NA	no	single function	productivity	biomass rates	AGB	(2) positive
82	thinning/burning	20+	(3) 15+	multiple	time	no	function_1	productivity	biomass rates	AGB	(2) positive
82	thinning/burning	20+	(3) 15+	multiple	time	no	function_2	recruitment	seedling	seedling density/richness	(3) no effect
83	salvage logging	3 to 4	(1) up to 5	multiple	time	no	function_1	trophic interactions	dispersal	bird activity	(4) negative
83	salvage logging	3 to 4	(1) up to 5	multiple	time	no	function_2	recruitment	seedling	seedling recruitment	(4) negative
97	fencing	16	(3) 15+	single	NA	no	single function	recruitment	seedling	seedling density/richness	(2) positive
106	planting	23	(3) 15+	single	NA	yes	single function	recruitment	both seed and seedling	seed and seedling density/richness	(5) unclear
117	planting	10	(2) 5 to 15	single	NA	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
120	planting	2	(1) up to 5	multiple	time	yes	single function	trophic interactions	facilitation	plant survival/growth	(2) positive
123	fencing	NA	NA	single	NA	no	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; decomposition	(2) positive
123	fencing	NA	NA	single	NA	no	function_2	productivity	biomass rates	litter production	(2) positive
123	fencing	NA	NA	single	NA	no	function_3	water relations	soil moisture	soil moisture	(2) positive
133	thinning/burning	2-3	(1) up to 5	single	NA	no	single function	recruitment	seedling	seedling density/richness	(2) positive
135	planting	18	(3) 15+	single	NA	yes	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial community	(2) positive
135	planting	18	(3) 15+	single	NA	yes	function_2	water relations	soil moisture	soil moisture	(2) positive
137	planting	1, 2, 4, 6, 7, 8, 12, 13, 14	(2) 5 to 15	multiple	space	yes	single function	trophic interactions	dispersal	seed removal	(1) similar to reference
138	salvage logging	1	(1) up to 5	single	NA	no	single function	recruitment	seedling	seedling density/richness	(4) negative
141	planting	10, 18, 25, 30	(3) 15+	multiple	space	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
141	planting	10, 18, 25, 30	(3) 15+	multiple	space	no	function_2	productivity	biomass rates	BGB; litter stock	(2) positive
150	thinning/burning	2	(1) up to 5	single	NA	yes	single function	productivity	biomass rates	AGB	(2) positive
155	thinning/burning	2	(1) up to 5	single	NA	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(5) unclear
155	thinning/burning	2	(1) up to 5	single	NA	no	function_2	productivity	biomass rates	AGB	(5) unclear
155	thinning/burning	2	(1) up to 5	single	NA	no	function_3	recruitment	seedling	seedling density/richness	(5) unclear
155	thinning/burning	2	(1) up to 5	single	NA	no	function_4	water relations	soil moisture	soil moisture	(5) unclear

ID	Restoration action	Restoration age (yrs)	Maximum time (yrs)	Frequency of measurement	Frequency: space or time	Reference	Number of functions	Function category	Ecological process	Variable measured	Result category
161	planting	5	(1) up to 5	single	NA	no	single function	nutrient cycling	soil biotic processes	fungi diversity	(2) positive
162	planting	10	(2) 5 to 15	single	NA	yes	single function	trophic interactions	mutualism	ant-plant interaction	(2) positive
168	planting	10, 22, 55	(3) 15+	multiple	space	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
168	planting	10, 22, 55	(3) 15+	multiple	space	no	function_2	productivity	biomass rates	litter stock	(1) similar to reference
168	planting	10, 22, 55	(3) 15+	multiple	space	no	function_3	recruitment	seedling	seedling density/richness	(2) positive
168	planting	10, 22, 55	(3) 15+	multiple	space	no	function_4	water relations	soil moisture	soil moisture	(2) positive
175	planting	20	(3) 15+	single	NA	no	single function	recruitment	seedling	seedling density/richness	(2) positive
178	planting/seeding	8, 9, 13	(2) 5 to 15	single	NA	yes	single function	trophic interactions	pollination	flower availability/visitation	(1) similar to reference
187	planting	12, 23, 55	(3) 15+	multiple	space	yes	single function	trophic interactions	pollination	flower availability/visitation	(2) positive
188	none	40	(3) 15+	single	NA	no	single function	trophic interactions	pollination	flower availability/visitation	(5) unclear
193	thinning/burning	4	(1) up to 5	single	NA	no	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial activity/diversity	(2) positive
193	thinning/burning	4	(1) up to 5	single	NA	no	function_2	water relations	soil moisture	soil moisture	(5) unclear
196	planting/seeding	aprox 8 and 17	(3) 15+	multiple	space	yes	single function	trophic interactions	mutualism	ant-plant interaction (for sugar)	(2) positive
197	planting	aprox 8 and 17	(3) 15+	multiple	space	yes	single function	trophic interactions	mutualism	ant-plant interaction (for sugar)	(5) unclear
207	planting	19	(3) 15+	single	NA	no	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
218	thinning/burning	1, 3	(1) up to 5	single	NA	no	single function	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial community	(5) unclear
237	weeding	2	(1) up to 5	single	NA	no	single function	recruitment	seed	seed bank/density	(2) positive
240	planting	16	(3) 15+	single	NA	no	single function	trophic interactions	herbivory	plant consumption	(1) similar to reference
245	planting	10	(2) 5 to 15	single	NA	no	single function	recruitment	seedling	seedling density/richness	(1) similar to reference
250	thinning/burning	1	(1) up to 5	single	NA	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
250	thinning/burning	1	(1) up to 5	single	NA	no	function_2	productivity	both biomass rates and stock	AGB; litterfall	(2) positive
250	thinning/burning	1	(1) up to 5	single	NA	no	function_3	water relations	soil moisture	soil moisture	(3) no effect
260	planting	20	(3) 15+	single	NA	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
260	planting	20	(3) 15+	single	NA	no	function_2	water relations	soil moisture	soil moisture	(4) negative
266	weeding	aprox 8	(1) up to 5	single	NA	no	single function	trophic interactions	pollination/herbivory	flower visitation; tree predation	(5) unclear
273	thinning/burning	1	(1) up to 5	single	NA	no	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
274	thinning/burning	aprox 2	(1) up to 5	single	NA	no	function_1	nutrient cycling	nutrient availability	nutrient loss	(2) positive
274	thinning/burning	aprox 2	(1) up to 5	single	NA	no	function_2	water relations	soil moisture	soil moisture	(2) positive
275	thinning/burning	2	(1) up to 5	single	NA	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(3) no effect
275	thinning/burning	2	(1) up to 5	single	NA	no	function_2	productivity	biomass rates	plant C/N/P fluxes	(3) no effect
287	thinning/burning	<2	(1) up to 5	single	NA	no	single function	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; fungi community	(2) positive
317	planting	3	(1) up to 5	single	NA	no	single function	trophic interactions	pollination	flower availability/visitation	(5) unclear
322	fencing	20, 30, 40, 60	(3) 15+	multiple	space	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools; nitrification rates	(3) no effect
322	fencing	20, 30, 40, 60	(3) 15+	multiple	space	no	function_2	water relations	soil moisture	soil moisture	(5) unclear
323	planting	20	(3) 15+	single	NA	no	single function	nutrient cycling	soil biotic processes	microbial biomass	(2) positive
325	none	1, 5, 10	(2) 5 to 15	multiple	space	yes	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
327	planting	10	(2) 5 to 15	single	NA	yes	single function	trophic interactions	dispersal	seed removal	(1) similar to reference

ID	Restoration action	Restoration age (yrs)	Maximum time (yrs)	Frequency of measurement	Frequency: space or time	Reference	Number of functions	Function category	Ecological process	Variable measured	Result category
328	planting	5	(1) up to 5	single	NA	yes	single function	trophic interactions	pollination	flower availability/visitation	(5) unclear
338	thinning/burning	<10, 30-60, 60+	(3) 15+	multiple	space	no	single function	productivity	biomass rates	AGB	(4) negative
344	none	10, 15, 30	(3) 15+	multiple	space	no	single function	productivity	biomass rates	litter stock	(2) positive
363	planting	3 to 4	(1) up to 5	single	NA	no	single function	trophic interactions	predation	animal foraging behavior	(5) unclear
365	planting	4, 6, 8	(2) 5 to 15	multiple	space	no	single function	productivity	biomass rates	litter stock	(2) positive
368	planting	2 to 26	(3) 15+	multiple	space	yes	function_1	nutrient cycling	nutrient availability	index	(2) positive
368	planting	2 to 26	(3) 15+	multiple	space	yes	function_2	water relations	infiltration	infiltration	(2) positive
379	none	45	(3) 15+	single	NA	yes	function_1	productivity	biomass rates	AGB	(1) similar to reference
379	none	45	(3) 15+	single	NA	yes	function_2	recruitment	seedling	seedling density/richness	(2) positive
382	planting	3-5, 8-10	(2) 5 to 15	multiple	space	no	single function	recruitment	seedling	seedling density/richness	(5) unclear
389	planting	1-10, 11-20, 21-30, 30+	(3) 15+	multiple	space	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
400	planting	15	(2) 5 to 15	single	NA	no	single function	recruitment	seedling	seedling density/richness	(5) unclear
402	planting	14	(2) 5 to 15	single	NA	no	single function	water relations	infiltration	infiltration	(2) positive
403	planting/seeding	5	(1) up to 5	single	NA	no	single function	productivity	biomass rates	AGB/BGB	(2) positive
410	planting/seeding	10, 15, 20	(3) 15+	multiple	time	no	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(5) unclear
420	none	<1	(1) up to 5	single	NA	yes	single function	recruitment	seedling	seedling density/richness	(1) similar to reference
425	planting	10 to 25	(3) 15+	multiple	space	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
425	planting	10 to 25	(3) 15+	multiple	space	no	function_2	water relations	infiltration	infiltration	(2) positive
430	planting	12, 30, 35	(3) 15+	multiple	space	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
435	planting	59	(3) 15+	multiple	time	no	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial community	(2) positive
435	planting	59	(3) 15+	multiple	time	no	function_2	water relations	surface runoff	surface runoff	(2) positive
454	NA	3 to 34	(3) 15+	single	NA	yes	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; decomposition	(2) positive
454	NA	3 to 34	(3) 15+	single	NA	yes	function_2	water relations	soil moisture	soil moisture	(5) unclear
456	planting	3	(1) up to 5	single	NA	yes	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(3) no effect
456	planting	3	(1) up to 5	single	NA	yes	function_2	productivity	biomass rates	litter production	(3) no effect
456	planting	3	(1) up to 5	single	NA	yes	function_3	recruitment	seedling	seedling density/richness	(3) no effect
456	planting	3	(1) up to 5	single	NA	yes	function_4	water relations	soil moisture	soil moisture	(3) no effect
457	planting	4	(1) up to 5	single	NA	yes	function_1	nutrient cycling	soil biotic processes	decomposition	(3) no effect
457	planting	4	(1) up to 5	single	NA	yes	function_2	productivity	biomass rates	litter production	(3) no effect
457	planting	4	(1) up to 5	single	NA	yes	function_3	recruitment	seedling	seedling density/richness	(3) no effect
457	planting	4	(1) up to 5	single	NA	yes	function_4	water relations	soil moisture	soil moisture	(3) no effect
470	planting	10 to 22	(3) 15+	multiple	space	yes	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
471	thinning/burning	aprox 1	(1) up to 5	single	NA	no	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(5) unclear
471	thinning/burning	aprox 1	(1) up to 5	single	NA	no	function_2	water relations	soil moisture	soil moisture	(2) positive
479	fencing	7, 12	(2) 5 to 15	multiple	space	no	function_1	trophic interactions	herbivory	protection from herbivory	(2) positive
479	fencing	7, 12	(2) 5 to 15	multiple	space	no	function_2	recruitment	seedling	seedling density/richness	(2) positive
481	thinning/burning	1-2	(1) up to 5	single	NA	no	function_1	nutrient cycling	soil biotic processes	fungi diversity	(4) negative
481	thinning/burning	1-2	(1) up to 5	single	NA	no	function_2	productivity	biomass rates	BGB	(4) negative
499	planting	18, 28, 38	(3) 15+	multiple	time	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
501	planting	3 a 5	(1) up to 5	single	NA	yes	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
501	planting	3 a 5	(1) up to 5	single	NA	yes	function_2	productivity	biomass rates	AGB; litter stock	(2) positive
501	planting	3 a 5	(1) up to 5	single	NA	yes	function_3	water relations	infiltration	infiltration	(3) no effect

ID	Restoration action	Restoration age (yrs)	Maximum time (yrs)	Frequency of measurement	Frequency: space or time	Reference	Number of functions	Function category	Ecological process	Variable measured	Result category
502	planting	4 to 53	(3) 15+	multiple	space	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
503	planting	26	(3) 15+	single	NA	yes	function_1	nutrient cycling	soil biotic processes	microbial community	(5) unclear
503	planting	26	(3) 15+	single	NA	yes	function_2	recruitment	seed	seed bank/density	(2) positive
504	fencing	aprox 4	(1) up to 5	single	NA	no	function_1	nutrient cycling	soil biotic processes	decomposition	(2) positive
504	fencing	aprox 4	(1) up to 5	single	NA	no	function_2	productivity	biomass rates	litter stock	(2) positive
504	fencing	aprox 4	(1) up to 5	single	NA	no	function_3	water relations	infiltration	infiltration	(2) positive
524	none	5	(1) up to 5	single	NA	yes	single function	recruitment	seedling	seedling density/richness	(5) unclear
528	planting	aprox 120	(3) 15+	single	NA	NA	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; soil biota activity	(5) unclear
528	planting	aprox 120	(3) 15+	single	NA	NA	function_2	recruitment	seedling	seedling density/richness	(5) unclear
533	planting	10, 20	(3) 15+	multiple	space	yes	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial community	(5) unclear
533	planting	10, 20	(3) 15+	multiple	space	yes	function_2	water relations	soil moisture	soil moisture	(5) unclear
537	planting	1, 2, 5, 10	(2) 5 to 15	multiple	space	no	single function	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial biomass	(2) positive
543	planting	15-25	(3) 15+	single	NA	yes	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial community	(1) similar to reference
543	planting	15-25	(3) 15+	single	NA	yes	function_2	water relations	soil moisture	soil moisture	(2) positive
544	planting	20	(3) 15+	single	NA	no	single function	productivity	biomass rates	AGB	(2) positive
548	planting	3.5 to 8.5	(2) 5 to 15	multiple	space	yes	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
551	planting	19	(3) 15+	single	NA	no	single function	productivity	biomass rates	AGB	(2) positive
560	planting	6	(2) 5 to 15	single	NA	yes	single function	trophic interactions	pollination	flower availability/visitation	(2) positive
584	perches	3	(1) up to 5	single	NA	no	single function	recruitment	both seed and seedling	seed and seedling density/richness	(2) positive
585	planting	NA	NA	single	NA	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
592	planting	aprox 15	(2) 5 to 15	single	NA	no	single function	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial biomass	(5) unclear
598	planting	19	(3) 15+	single	NA	no	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
003a	planting	5, 11, 21, 30	(3) 15+	multiple	space	yes	function_1	nutrient cycling	both nutrient and biotic processes	soil C, N, P or OM pools; microbial biomass	(2) positive
003a	planting	5, 11, 21, 30	(3) 15+	multiple	space	yes	function_2	productivity	biomass rates	AGB/BGB	(2) positive
003a	planting	5, 11, 21, 30	(3) 15+	multiple	space	yes	function_3	water relations	soil moisture	soil moisture	(5) unclear
019a	planting	15, 25, 57	(3) 15+	multiple	space	NA	single function	trophic interactions	dispersal	seed dispersal networks	(2) positive
028a	planting	6	(2) 5 to 15	single	NA	yes	function_1	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(2) positive
028a	planting	6	(2) 5 to 15	single	NA	yes	function_2	productivity	biomass rates	AGB/BGB	(2) positive
044a	thinning/burning	16	(3) 15+	multiple	time	no	single function	water relations	surface runoff	surface runoff	(2) positive
052a	planting	17 to 20	(3) 15+	single	NA	no	single function	productivity	biomass rates	growth rate (biomass)	(2) positive
060a	planting	3 to 22	(3) 15+	multiple	space	yes	single function	water relations	soil moisture	soil moisture	(2) positive
066a	weeding	1	(1) up to 5	single	NA	no	single function	recruitment	seedling	seedling density/richness	(2) positive
084a	thinning/burning	5	(1) up to 5	single	NA	no	single function	recruitment	seedling	seedling density/richness	(2) positive
092a	thinning/burning	10	(2) 5 to 15	single	NA	no	single function	productivity	biomass rates	AGB	(2) positive
103a	planting	10, 22, 55	(3) 15+	multiple	space	yes	single function	recruitment	seedling	seedling density/richness	(2) positive
106a	planting	7	(2) 5 to 15	single	NA	no	single function	recruitment	seedling	seedling density/richness	(3) no effect
125a	planting	5	(1) up to 5	single	NA	no	single function	productivity	biomass rates	litterfall	(1) similar to reference
138a	planting	4	(1) up to 5	multiple	time	yes	single function	nutrient cycling	nutrient availability	soil C, N, P or OM pools	(5) unclear

ANEXO II

Tabela AII. Valor médio por espécie dos atributos funcionais utilizados no trabalho: área foliar (LA), área foliar específica (SLA), conteúdo de matéria seca foliar (LDMC), conteúdo de nitrogênio (LNC) e fósforo foliar (LPC), massa de semente (SM), tamanho de fruto (FS), altura máxima (MH) e densidade da madeira (WD). Há indicação do sítio (Cachoeirinha – Cac, Canela – Can e/ou Santa Tereza – Ste) e tratamento (Trat – floresta ou restauração) onde as espécies foram amostradas. O número de árvores amostradas (#ind) se refere somente aos atributos foliares e indica o número de indivíduos coletados em florestas da região sul. Observações específicas sobre as médias por espécie são indicadas na coluna “Detalhes”.

Tabela AII. Valor médio por espécie dos atributos funcionais utilizados no trabalho: área foliar (LA), área foliar específica (SLA), conteúdo de matéria seca foliar (LDMC), conteúdo de nitrogênio (LNC) e fósforo foliar (LPC), massa de semente (SM), tamanho de fruto (FS), altura máxima (MH) e densidade da madeira (WD). Há indicação do sítio (Cachoeirinha – Cac, Canela – Can e/ou Santa Tereza – Ste) e tratamento (Trat – floresta ou restauração) onde as espécies foram amostradas. O número de árvores amostradas (#ind) se refere somente aos atributos foliares e indica o número de indivíduos coletados em florestas da região sul. Observações específicas sobre as médias por espécie são indicadas na coluna "Detalhes".

Espécie	**#ind**	**LA (mm^2)**	**SLA (mm^2 mg^{-1})**	**LDMC (mg g^{-1})**	**LNC (mg mg^{-1})**	**LPC (mg mg^{-1})**	**SM (g)**	**FS (cm^2)**	**MH (m)**	**WD (g cm^{-3})**	**Sítio**	**Trat**	**Detalhes***
Actinostemon concolor	10	24,12	9,41	390,56	1,14	0,07	0,3800	6,50	20,0	0,66	Can	Floresta	[a] SM/FS
Aegiphila integrifolia	5	37,25	6,10	267,69	1,88	0,14	0,1088	21,50	15,0	0,43	Cac	Floresta	[d] SM/FS
Alchornea triplinervia	7	26,50	8,04	430,56	1,82	0,13	0,0211	8,00	28,0	0,47	Can	Ambos	[a] SM/FS
Allophylus edulis	26	7,36	14,80	397,68	1,39	0,13	0,0454	10,52	19,0	0,65	Todos	Ambos	
Allophylus guaraniticus	6	3,33	16,11	384,78	1,47	0,16	0,0182	5,00	15,0	0,58	Ste	Floresta	[a] SM/FS
Annona rugulosa	6	23,05	22,09	288,73	2,45	0,12	0,5742	35,03	14,0	0,46	Can	Floresta	[b] FS
Annona sp,	0	25,73	14,61	350,30	2,65	0,16	0,3220	35,03	18,0	0,51	Cac	Restaur	[b] All
Annona sylvatica	6	26,28	14,00	367,21	3,10	0,18	0,1459	35,03	16,0	0,67	Cac	Floresta	[b] FS; [d] WD
Apuleia leiocarpa	12	4,85	14,67	370,10	2,80	0,34	0,0042	32,10	42,0	0,80	Cac	Restaur	
Araucaria angustifolia	17	1,29	5,59	374,25	0,91	0,10	5,4878	175,00	42,0	0,48	Ste	Restaur	[a] SM/FS
Aspidosperma australe	11	13,05	12,92	357,55	1,90	0,08	0,2000	37,50	33,0	0,72	Cac	Restaur	[a] SM/FS
Ateleia glazioviana	7	6,79	19,64	300,00	2,27	0,18	0,0544	16,25	25,0	0,65	Can	Restaur	[a] SM/FS; [d] LNC/LPC
Baccharis semiserrata	5	3,38	13,23	366,01	2,27	0,18	0,1338	17,36	7,0	0,61	Can	Restaur	[a] SM/FS/MH; [d] LNC/LPC/WD
Banara parviflora	5	12,04	13,62	332,30	2,10	0,17	0,0008	3,00	16,0	0,60	Can	Restaur	[a] SM/FS; [c] All
Banara tomentosa	12	19,56	20,65	332,22	2,50	0,17	0,0008	3,00	16,0	0,60	Ste	Floresta	[a] SM/FS
Bauhinia forficata	6	60,69	15,64	315,35	4,30	0,57	0,0828	112,00	21,0	0,57	Cae, Ste	Ambos	[a] SM/FS
Blepharocalyx salicifolius	18	3,53	9,97	438,15	1,60	0,09	0,0154	9,00	20,0	0,71	Cac, Can	Ambos	[a] SM/FS
Boehmeria caudata	10	55,57	40,33	191,43	2,92	0,42	0,0007	2,55	6,0	0,36	Can	Floresta	[a] SM/FS
Cabralea canjerana	8	33,97	16,64	313,78	2,11	0,15	0,1651	10,26	25,0	0,54	Can	Ambos	
Campomanesia xanthocarpa	17	21,87	12,83	413,26	1,29	0,13	0,0585	19,17	28,0	0,86	Cae, Ste	Ambos	[a] SM/FS
Casearia decandra	20	6,57	15,68	503,51	2,00	0,13	0,0213	9,00	25,0	0,66	Cac, Can	Floresta	[a] SM/FS
Casearia sylvestris	19	18,91	12,62	407,30	2,28	0,14	0,0119	5,07	22,0	0,71	Todos	Ambos	[a] SM
Cedrela fissilis	11	38,08	17,60	337,22	3,02	0,30	0,0280	48,75	30,0	0,49	Todos	Ambos	[a] SM/FS
Celtis iguanaea	4	12,72	10,34	406,81	2,60	0,11	0,2182	5,80	12,0	0,66	Cac, Can	Ambos	[a] FS

Espécie	**#ind**	**LA (mm^2)**	**SLA (mm^2 mg^{-1})**	**LDMC (mg g^{-1})**	**LNC (mg mg^{-1})**	**LPC (mg mg^{-1})**	**SM (g)**	**FS (cm^2)**	**MH (m)**	**WD (g cm^{-3})**	**Sítio**	**Trat**	**Detalhes***
Cestrum intermedium	8	22,40	22,05	234,40	4,00	0,23	0,0115	6,86	15,0	0,61	Can	Floresta	[d] WD
Chrysophyllum marginatum	11	6,28	10,70	401,59	1,50	0,12	0,3529	12,00	25,0	0,70	Cac, Can	Ambos	[a] FS; [b] SM
Citharexylum myrianthum	8	49,14	12,25	320,48	2,00	0,27	0,7880	12,76	24,0	0,60	Can	Ambos	
Citharexylum solanaceum	0	30,99	9,02	379,61	1,85	0,20	0,7880	25,00	15,0	0,70	Can	Restaur	[a] FS
Citrus sinensis	4	63,47	10,11	425,05	2,27	0,18	0,1200	80,00	5,0	0,78	Can	Floresta	[a] SM/FS; [d] LNC/LPC
Citrus sp	0	63,47	10,11	425,05	2,21	0,17	0,1200	80,00	5,0	0,78	Ste	Floresta	[a] SM/FS; [d] LNC/LPC
Cordia americana	15	8,80	15,19	414,77	5,20	0,16	0,3020	5,14	27,0	0,69	Todos	Ambos	
Cordia trichotoma	10	34,75	14,86	370,38	2,30	0,19	0,0284	6,17	31,0	0,60	Ste	Restaur	[a] SM/FS
Cupania vernalis	15	24,34	11,08	418,10	1,72	0,19	0,1573	14,30	25,0	0,66	Todos	Ambos	
Dalbergia frutescens	5	10,44	16,33	265,36	2,27	0,18	0,0005	35,25	18,0	0,82	Can	Floresta	[a] SM/FS; [c] All; [d] LNC/LPC
Dasyphyllum spinescens	5	10,44	16,33	265,36	2,27	0,18	0,0005	17,50	18,0	0,83	Can	Restaur	[a] SM/FS; [d] LNC/LPC
Diospyros inconstans	7	11,96	11,97	388,93	1,90	0,13	0,2499	18,80	13,0	0,83	Can	Ambos	
Enterolobium contortisiliquum	6	0,39	12,15	439,29	2,70	0,14	0,1802	52,50	24,0	0,40	Can	Restaur	[a] SM/FS
Eriobotrya japonica	1	134,11	9,20	380,92	2,21	0,17	0,7500	50,00	8,0	0,88	Ste	Floresta	[a] SM/FS; [d] LNC/LPC
Erythrina falcata	8	40,17	13,91	318,49	3,10	0,20	0,6452	87,50	25,0	0,32	Can	Ambos	[a] SM/FS
Erythroxylum argentinum	6	9,66	10,48	439,26	2,20	0,35	0,0410	6,60	7,0	1,00	Cac, Can	Ambos	
Erythroxylum deciduum	8	13,41	13,39	349,92	3,00	0,30	0,0410	7,50	20,0	0,81	Cac	Ambos	[a] FS; [b] SM
Escalonia bifida	5	6,51	11,33	333,59	1,82	0,19	0,0005	3,67	9,0	0,64	Ste	Restaur	[a] SM/FS
Eucalyptus sp	1	34,60	13,76	364,35	2,27	0,18	0,0410	7,00	40,0	0,66	Can	Restaur	[a] SM/FS; [d] LNC/LPC
Eugenia hiemalis	0	14,31	10,20	408,12	1,54	0,10	0,4287	19,47	17,7	0,79	Cac	Floresta	[a] SM; [b] All
Eugenia ramboi	4	5,60	14,73	424,86	1,54	0,10	0,2045	10,00	20,0	0,79	Can	Ambos	[a] FS; [b] LNC/LPC/SM
Eugenia rostrifolia	4	9,68	19,08	446,61	1,13	0,07	0,2045	12,50	32,5	0,80	Can	Ambos	[a] FS; [b] SM
Eugenia uniflora	14	6,54	14,05	413,78	1,60	0,10	0,4287	15,00	18,0	0,83	Cac, Ste	Restaur	[a] SM; [b] FS
Eugenia uruguayensis	14	8,56	7,90	418,20	1,50	0,12	0,4287	10,75	16,5	0,79	Ste	Floresta	[a] SM/FS; [c] WD
Eugenia verticillata	8	10,73	10,49	348,66	1,29	0,11	0,4287	19,47	12,0	0,79	Cac	Floresta	[a] SM; [b] FS/WD
Faramea montevidensis	5	20,72	12,20	370,39	1,50	0,05	0,0588	6,00	12,0	0,67	Cac	Floresta	[a] FS; [d] WD
Ficus adhatodifolia	8	90,88	9,58	281,07	2,12	0,16	0,0002	25,16	30,0	0,58	Can	Restaur	[a] SM
Ficus luschnathiana	18	32,95	7,90	361,95	2,25	0,17	0,0002	11,36	26,0	0,42	Cac	Floresta	[a] SM

Espécie	**#ind**	**LA (mm^2)**	**SLA (mm^2 mg^{-1})**	**LDMC (mg g^{-1})**	**LNC (mg mg^{-1})**	**LPC (mg mg^{-1})**	**SM (g)**	**FS (cm^2)**	**MH (m)**	**WD (g cm^{-3})**	**Sítio**	**Trat**	**Detalhes***
Handroanthus albus	6	44,19	10,15	370,29	2,60	0,22	0,0117	122,50	25,0	1,10	Ste	Restaur	[a] SM/FS
Handroanthus heptaphyllus	6	17,25	12,83	436,77	2,40	0,16	0,1111	132,50	20,0	0,98	Ste	Restaur	[a] SM/FS
Hovenia dulcis	8	35,29	16,55	332,82	2,12	0,16	0,2700	6,50	25,0	0,54	Cae, Ste	Ambos	[a] FS; [d] SM
Inga marginata	11	15,43	11,93	427,48	2,62	0,15	0,9998	56,25	26,0	0,58	Todos	Ambos	[a] SM/FS
Inga sessilis	12	34,07	12,33	457,57	1,88	0,14	0,2449	7,73	25,0	0,43	Can	Ambos	[b] SM
Inga vera	0	40,93	13,49	450,84	1,88	0,14	1,2796	77,50	25,0	0,43	Cac	Restaur	[a] SM/FS
Jacaranda micrantha	10	9,35	18,54	398,05	2,40	0,13	0,0080	65,00	26,0	0,48	Cac	Restaur	[a] SM/FS
Lithraea brasiliensis	14	7,00	9,38	432,01	1,40	0,13	0,0392	55,00	22,0	0,98	Cac	Floresta	[a] SM
Lonchocarpus campestris	8	5,78	17,08	447,75	2,80	0,14	0,1250	40,00	25,0	0,89	Ste	Ambos	[a] SM/FS
Luehea divaricata	13	25,56	12,52	390,90	1,68	0,23	0,0028	14,96	26,0	0,56	Todos	Ambos	
Machaerium paraguariense	8	8,45	13,84	360,71	3,90	0,24	0,0915	60,00	25,0	0,50	Cae, Ste	Ambos	[a] FS
Machaerium stipitatum	8	2,86	13,56	457,98	2,44	0,14	0,0915	2,76	23,0	0,65	Cae, Ste	Ambos	
Matayba elaeagnoides	8	13,96	12,46	332,27	1,98	0,18	0,1523	13,77	23,0	0,81	Cac, Can	Floresta	
Miconia sellowiana	5	7,79	9,54	432,28	1,40	0,06	0,6580	2,50	7,5	0,66	Cac	Floresta	[a] SM/FS; [b] WD
Mimosa bimucronata	5	0,18	16,43	458,08	1,95	0,15	0,0112	15,52	13,0	0,61	Cac	Ambos	[a] SM; [c] FS; [d] LNC/LPC
Morus nigra	4	50,64	15,43	335,00	2,21	0,17	0,4063	21,50	12,0	0,52	Ste	Restaur	[a] SM/FS; [d] LNC/LPC
Myrcia glabra	5	24,45	7,41	359,15	1,30	0,06	0,2127	7,94	23,0	0,83	Cac	Floresta	[a] SM; [b] FS/WD
Myrcia multiflora	0	14,47	8,15	408,33	1,35	0,08	0,0172	7,94	19,0	0,83	Cac	Floresta	[b] All
Myrcia palustris	9	4,38	6,21	398,21	1,20	0,10	0,0179	6,77	17,0	0,83	Cac	Floresta	[b] WD
Myrciantes gigantea	4	9,79	6,28	430,37	2,40	0,09	0,3132	10,75	18,0	0,91	Can	Floresta	[a] FS; [c] SM
Myrsine coriacea	21	9,10	11,26	353,92	1,82	0,11	0,0116	3,95	19,0	0,59	Todos	Ambos	
Myrsine lorentziana	25	15,09	8,79	355,68	1,35	0,12	0,0116	4,55	12,0	0,41	Cac, Can	Ambos	[c] SM
Myrsine umbellata	10	57,97	7,57	359,59	1,09	0,06	0,0116	2,80	20,0	0,86	Todos	Ambos	[a] FS; [c] SM
Nectandra grandiflora	6	14,13	5,60	468,07	1,66	0,15	1,1111	9,75	20,0	0,61	Cac	Floresta	[a] SM/FS; [d] LNC/LPC
Nectandra megapotamica	16	10,57	10,34	437,74	2,06	0,12	0,1845	9,75	27,0	0,75	Cae, Ste	Ambos	[a] FS; [c] SM
Ocotea porosa	8	13,94	8,94	462,66	2,50	0,10	1,2821	11,50	21,0	0,57	Ste	Floresta	[a] SM/FS
Ocotea puberula	10	15,66	9,84	413,05	3,04	0,20	0,1839	8,79	30,0	0,43	Todos	Ambos	
Ocotea pulchella	15	7,42	8,04	495,97	1,70	0,14	0,3333	8,17	25,0	0,65	Cac	Floresta	[a] SM/FS
Parapiptadenia rigida	12	0,18	16,70	457,65	2,21	0,15	0,0299	61,25	35,0	0,85	Todos	Ambos	[a] SM/FS; [d] LNC/LPC

Espécie	**#ind**	**LA (mm^2)**	**SLA (mm^2 mg^{-1})**	**LDMC (mg g^{-1})**	**LNC (mg mg^{-1})**	**LPC (mg mg^{-1})**	**SM (g)**	**FS (cm^2)**	**MH (m)**	**WD (g cm^{-3})**	**Sítio**	**Trat**	**Detalhes***
Peltophorum dubium	7	0,52	12,66	437,57	2,21	0,17	0,0476	42,50	35,0	0,75	Todos	Restaur	[a] SM/FS; [d] LNC/LPC
Phytolacca dioica	5	111,04	15,28	186,68	4,00	0,32	0,0056	6,50	26,0	0,44	Can	Floresta	[a] FS
Pisonia zapallo	5	40,35	16,38	183,00	1,88	0,14	0,1471	5,00	20,0	0,35	Can	Floresta	[a] SM/FS
Prunus myrtifolia	9	14,69	9,27	413,80	1,88	0,14	0,0783	7,48	23,0	0,74	Cac, Ste	Ambos	
Psidium cattleyanum	8	19,07	5,21	375,73	1,01	0,12	0,0137	22,50	18,0	1,12	Cac	Restaur	[a] SM/FS
Psychotria brachyceras	5	19,21	25,82	234,57	2,19	0,11	0,0161	7,40	18,7	0,61	Can	Floresta	[b] LNC/LPC/SM/FS
Quillaja brasiliensis	6	6,48	7,44	378,30	1,50	0,13	0,0038	2,30	18,0	0,76	Can	Restaur	[a] SM/FS
Sapium glandulosum	16	20,51	9,04	290,08	1,96	0,15	0,0590	11,71	31,0	0,44	Can	Ambos	[a] SM
Schinus polygamus	0	3,86	8,45	459,16	2,27	0,18	0,0150	3,75	9,0	0,60	Can	Restaur	[a] SM/FS; [d] LPC
Schinus terebinthifolius	10	5,81	9,46	400,47	1,60	0,18	0,0150	3,90	16,0	0,80	Cac, Can	Ambos	[a] FS; [c] SM
Sebastiania brasiliensis	6	9,00	14,98	323,21	1,80	0,20	0,0043	7,06	18,0	0,67	Cac	Floresta	[a] SM; [c] All
Sebastiania serrata	7	7,64	11,38	422,94	1,90	0,12	0,0043	7,06	19,0	0,64	Cac	Ambos	
Solanum mauritianum	5	29,72	17,53	206,80	3,60	0,27	0,0057	10,00	20,0	0,53	Can	Restaur	[a] FS; [b] SM
Solanum pseudoquina	9	16,66	14,84	304,36	2,95	0,22	0,0057	21,79	22,0	0,53	Can	Restaur	[b] SM
Solanum sanctaecatharinae	8	31,13	18,18	300,98	3,14	0,21	0,0250	13,64	12,0	0,64	Can	Floresta	[a] SM/FS
Sorocea bonplandii	8	23,18	10,53	429,23	1,23	0,10	0,1595	12,55	24,0	0,62	Cac, Ste	Floresta	
Styrax leprosus	17	10,24	8,78	448,84	1,40	0,08	0,1250	9,25	20,0	0,41	Can	Restaur	[a] SM/FS
Syagrus romanzoffiana	3	78,21	7,85	473,66	2,00	0,15	3,5278	11,50	26,0	0,81	Cac	Floresta	[a] SM/FS
Tecoma stans	5	10,60	21,70	315,62	2,27	0,18	0,0800	105,00	7,0	0,46	Cae, Ste	Restaur	[a] SM/FS/MH; [d] LNC/LPC/WD
Trema micrantha	14	14,67	12,49	339,57	2,25	0,23	0,0038	3,64	18,5	0,35	Cac, Can	Ambos	
Trichilia claussenii	10	22,77	12,74	440,35	1,82	0,11	0,4251	11,04	18,0	0,68	Cae, Ste	Ambos	
Trichilia elegans	5	5,07	18,30	397,76	2,12	0,14	0,4251	6,70	13,0	0,68	Ste	Floresta	[a] FS; [b] LNC/LPC; [c] SM/WD
Urera baccifera	8	452,10	23,10	146,80	3,80	0,47	0,0007	1,85	16,0	0,17	Can	Ambos	[a] FS
Vitex megapotamica	11	10,81	12,29	399,74	1,50	0,10	0,2602	16,22	25,0	0,67	Cac	Ambos	
Xylosma pseudosalzmanii	5	9,33	10,91	393,44	1,32	0,12	0,0093	3,78	18,0	0,65	Cae, Ste	Ambos	
Zanthoxylum fagara	14	2,02	12,95	281,94	1,95	0,17	0,0063	3,79	22,0	0,65	Cac	Ambos	[a] SM; [c] FS; [d] LNC
Zanthoxylum petiolare	2	18,45	15,24	355,36	1,50	0,29	0,0063	3,79	27,0	0,90	Can	Restaur	
Zanthoxylum rhoifolium	19	5,87	9,91	379,34	1,68	0,10	0,0063	3,79	23,0	0,57	Cac, Can	Ambos	

* [a] Origem: literatura; [b] Média para o gênero; [c] Valor de espécie similar do mesmo gênero; [d] Média do sítio de amostragem.