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ORIGINAL ARTICLE

Forest restoration after severe degradation by coal mining: lessons from the first years of monitoring

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Abstract

Restoration after mining often requires strong interventions, including soil reconstruction, which makes vegetation establishment a challenge. We analyzed regeneration of woody plant species in the first years of restoration in areas severely degraded by coal mining in the south Brazilian Atlantic rainforest. At the four restoration sites, we collected data on cover of the herbaceous layer (including invasive grasses) and on abundance and richness of introduced trees and of spontaneously establishing woody plants. We also evaluated soil chemical features at all sites. We compared functional characteristics of the woody regeneration with nearby forest remnants (target communities) and evaluated the dynamics of regeneration over 3 years by principal coordinates analyses. The influence of biotic and abiotic variables for the regeneration of woody species was analyzed by partial redundancy analysis. We found high variation in community composition and structure among restored sites. Most of this variation was explained by variables related to soil chemistry and introduced trees. Over time, an increase in woody species establishment could be observed, and woody species communities appear to be at the start of trajectories toward target communities. Fertilization of soil, as commonly applied in restoration, seems to increase cover of exotic grasses, which clearly impedes the development of planted trees and woody species regeneration. Although the restoration of abandoned mining areas is a challenge due to the severe degradation, our results—despite the short period of observation—allow for the conclusion that restoration is possible, even with high initial costs. We highlight the importance of monitoring the initial process of restoration and of (re)defining intermediate goal and project targets, following an adaptive management approach.

Keywords Atlantic rainforest · Invasive grasses · Soil fertilization · Tree planting · Woody regeneration

1 Introduction

Mining is an activity with strong impacts on ecosystems, due to severe problems with pollution at the mining sites itself and in the surroundings during the mining process

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(Silva et al. 2011, 2013), the often complete destruction of the ecosystems where mining takes place (Adibee et al. 2013) and the possible long-term consequences of both. In consequence, the ecological restoration of areas affected by mining activities can be very difficult (Zipper et al. 2011; Adibee et al. 2013). Reduction and containment of pollution and repairing past environmental damage usually are the principal actions before restoration of the destroyed vegetation and ecosystems itself can be initiated. However, severe limitations related to the establishment of native species and initiation of natural succession processes at former mining sites are common (Fields-Johnson et al. 2012; Zhenqi et al. 2012; Bauman et al. 2013). Often, these limitations are a consequence of strong interventions that are required to change the abiotic and biotic characteristics of the degraded systems, such as soil reconstruction.

The introduction of trees by plantings is a widely used strategy to overcome recruitment limitations (Omeja et al. 2011). Tree plantings also enhance succession through the attraction of seed-dispersing animals and the creation of microclimatic conditions favorable for establishment of forest plants (Martinez-Ramos and Soto-Castro 1993; Parrotta et al. 1997a). However, after surface-mining activities, the newly constructed substrate often does not present adequate conditions regarding physical structure and chemical properties, and generally is strongly compacted (Kämpf et al. 1997; Bassett et al. 2005), reducing survival of plants. To reduce erosion and to gradually improve soil conditions, a first vegetation cover is often established by planting exotic grasses, many of them considered invasive. These grasses can constitute an additional difficulty for post-mining vegetation recovery (Nyamai et al. 2011; Bennett et al. 2012): Invasive grasses limit the establishment and diversity of native plant species because they are strong competitors. Also, they often increase the incidence of fire (Veldman et al. 2009), which further impedes the colonization by woody species, the target species of restoration in the case of forest ecosystems (Martínez-Garza et al. 2005; McGlone et al. 2012).

Depending on the specific environmental features at a restoration site, on the disturbance history of the site and on the first restoration actions, the successional trajectories of plant communities under restoration areas can vary widely (Chazdon et al. 2007). Differences to the planned or desired trajectories may already become obvious in early restoration phases. In highly impacted lands, the monitoring of restoration in the first years is especially important, as initial successional pathways may drive regeneration processes and vegetation dynamics for long periods (Zipper et al. 2011; Fields-Johnson et al. 2012; Zhenqi et al. 2012; Bauman et al. 2013). Therefore, an early monitoring is crucial for any potential implementation of adaptive management actions that can further allow the expected development of the restoration site (Lindenmayer and Likens 2009). Further, a better understanding of the role of the main biotic and abiotic limitations during all restoration phases is important to improve ecological theory and practice (Block et al. 2001; Miller and Hobbs 2007).

Here, we present results of vegetation monitoring in the first years of restoration in a region severely affected by coal mining in the southern part of the Brazilian Atlantic rainforest, in the region around Criciúma (Santa Catarina state). Mining has been conducted in this region for more than 100 years (Silva et al. 2011). For many decades, before the more recent rise of environmental consciousness, no actions to reduce pollution or to restore these sites had been undertaken at all in these areas. Waste material from coal mines was deposited without any precaution or measures to impede or reduce environmental pollution. Runoff water from polluted areas and from mines has caused severe contamination of watersheds in the region (Silva et al. 2013). At present, pH values in rivers may reach 3.0, and environmental conditions present severe health risk for the human population in the region (Santos et al. 2008; Silva et al. 2011, 2013). Altogether, the region contains 6500 ha of areas degraded by coal mining (Brasil 2015). In 2000, restoration of all riparian zones in the region became mandatory (Brasil 2013), and remnants of natural vegetation were defined as reference sites. Since this time, restoration projects have been planned and implemented, but restoration success has not been assessed thoroughly in these areas characterized by high environmental damage (Rocha-Nicoleite et al. 2017).

We studied the natural regeneration of woody species communities in four areas undergoing ecological restoration, comparing species composition and abundance patterns in relation to canopy structure (mainly formed by planted trees), soil features and cover of herbaceous species, including exotic grasses. We looked specifically at the first years (until 10 years) of the restoration projects, and evaluated vegetation dynamics and trajectories over 3 years. Our questions were: (1) Do the four restoration sites present differences in species composition, abundance and ecological traits of regenerating woody species, and how much do restoration sites differ from reference areas? (2) Which subset of variables (canopy structure, soil features or herbaceous cover) best explains these differences? (3) How distinct are the short-term vegetation trajectories among the restoration sites? Our main expectations are a positive response of species composition and abundance to the biotic variables, such as higher vegetation cover and higher richness of regenerating trees at sites with higher structured canopy and lower cover of exotic grasses, due to increased seed arrival, higher seedling establishment and reduced competition under these conditions. We also expected that the oldest area (10 years) should be more similar to the reference areas, e.g., present higher species richness and a lower proportion of shrubs, indicating an already more advanced position on the successional trajectory toward reference conditions.

2 Materials and methods

Study region – The study was conducted in southern Santa Catarina state, Brazil, close to the city of Criciúma. Study sites are under humid subtropical climate conditions, with average annual temperature of 19 °C and rainfall average of about 1600 mm (Back 2009; Alvares et al. 2013). Originally, this region was completely covered by Atlantic rainforest (Ribeiro et al. 2009; Teixeira et al. 2009; Colombo and Joly 2010), part of a global biodiversity hotspot (Myers et al. 2000; Eisenlohr et al. 2015).

Our research was conducted at four sites (A: 28°26′31″S, 49°23′49″W; B: 28°26′60″S, 49°24′56″W; C: 28°25′53″S, 49°25′26″W; D: 28°35′01″S, 49°25′09″W) currently under ecological restoration. All sites had been degraded by surface coal mining with deposition of spoils in riparian zones, decades ago. The original vegetation at these sites is riparian forest with high species richness, especially of Myrtaceae and Lauraceae (Colonetti et al. 2009). The principal goal of restoration is the reestablishment of the pre-mining forest communities. As reference areas, we studied two riparian forest remnants without any history of mining (areas R1 and R2), situated in the same region (R1: 28°34′S–49°24′W; R2: 28°26′S–49°25′W) (Fig. 1).

The restoration actions at the four study sites followed the general procedures applied in the region: The first step was the removal of spoils to stop ongoing contamination. After this, a new substrate, composed of clay or sand (depth ca. 2 m), was constructed in order to provide support for vegetation and to define the topography. Soil construction was finished with the addition of a thin layer organic matter (ca. 2 cm), usually peat and broiler litter. Then, the first vegetation cover was established by sowing exotic grasses in order to rapidly cover the soil, which is required by environmental agency, followed by planting or seeding of native trees.

At the studied sites, the following exotic grasses were sowed: in area A *Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webste (Poaceae; 18 kg ha^{-1}), in areas B and C *Avena sativa* L. (Poaceae) and *Lolium multiflorum* Lam. (Poaceae; 30 kg ha^{-1} of each species) and in area D *Melinis minutiflora* P. Beauv. (Poaceae; 15 kg ha^{-1}). Following this, 30 native tree species were planted with a density of 2500 individuals per hectare in areas A, B and C. In area D, one native tree, *Mimosa scabrella* Benth. (Fabaceae), was sowed (3 kg ha^{-1} with latter cutting of some individuals to reach a density of around 5000 individuals per hectare) and seedlings of 16 species were planted at 20 nuclei. These interventions were carried out between 2009 and 2010 in areas A, B and C (coal mined between 1975 and 1997) and between 2002 and 2005 in area D (coal mined between 1950 and 1989). Due to the high level of contamination, virtually no vegetation development had occurred in the period from end of coal mining until the restoration interventions.

Vegetation surveys – The studied areas differed in terms of size (from 0.6 to 1.2 ha); thus, the number of sampling units per area was distinct: We established six permanent plots in areas B and D, and ten plots in areas A and C (plot size: 10 by 30 m). In these plots, we recorded all survived planted trees and all naturally recruited woody plants with diameter at breast height (DBH) $\geq$ 5 cm (upper stratum, used to characterize the canopy structure in our study). The natural regeneration stratum, composed of woody individuals with height $\geq$ 50 cm and $\leq$ 5 cm DBH, was sampled in three subplots of 5 × 5 m. In these subplots, we also estimated the cover of three categories of herbs: exotic grasses, native grasses and forbs. The regeneration stratum and the categories of herbs were evaluated three times (A, B and C areas: 18, 30 and 40 months after tree planting; D area: 8, 9 and 10 years after tree planting).

The survey of the reference areas was important to know the forest structure and the species composition of nearby remnants, as no published studies on composition of riparian forests in the region are available. We established 30 plots of 10 × 10 m in each remnant forest (R1 and R2) to sample the upper stratum (DBH $\geq$ 5 cm), each with one subplot of 5 × 5 m for the regenerating stratum (height $\geq$ 50 cm and < 5 cm DBH). As the structure and composition of these reference areas obviously differed considerably from the restoration sites, we only compared them by describing some principal characteristics.

All plant species were identified in the field or later by help of literature, or consultation of herbaria and specialists. Classification into families follows APG IV (2016). For all regenerating woody species, selected ecological traits (dispersal syndrome; species origin; successional stage) were compiled from the literature (Carvalho 2003, 2006, 2008).

Analysis of soil properties – Samples of the surface soil layer (0–20 cm) were collected in one subplot of 5 × 5 m per plot at the restoration sites for evaluation of chemical soil chemistry parameters. Laboratory methods followed Tedesco et al. (1995). Samples were dried at a temperature of 60 °C for 24 h. Soil pH was determined in water solution by a potentiometer using soil/solution ratio 1:1, soil

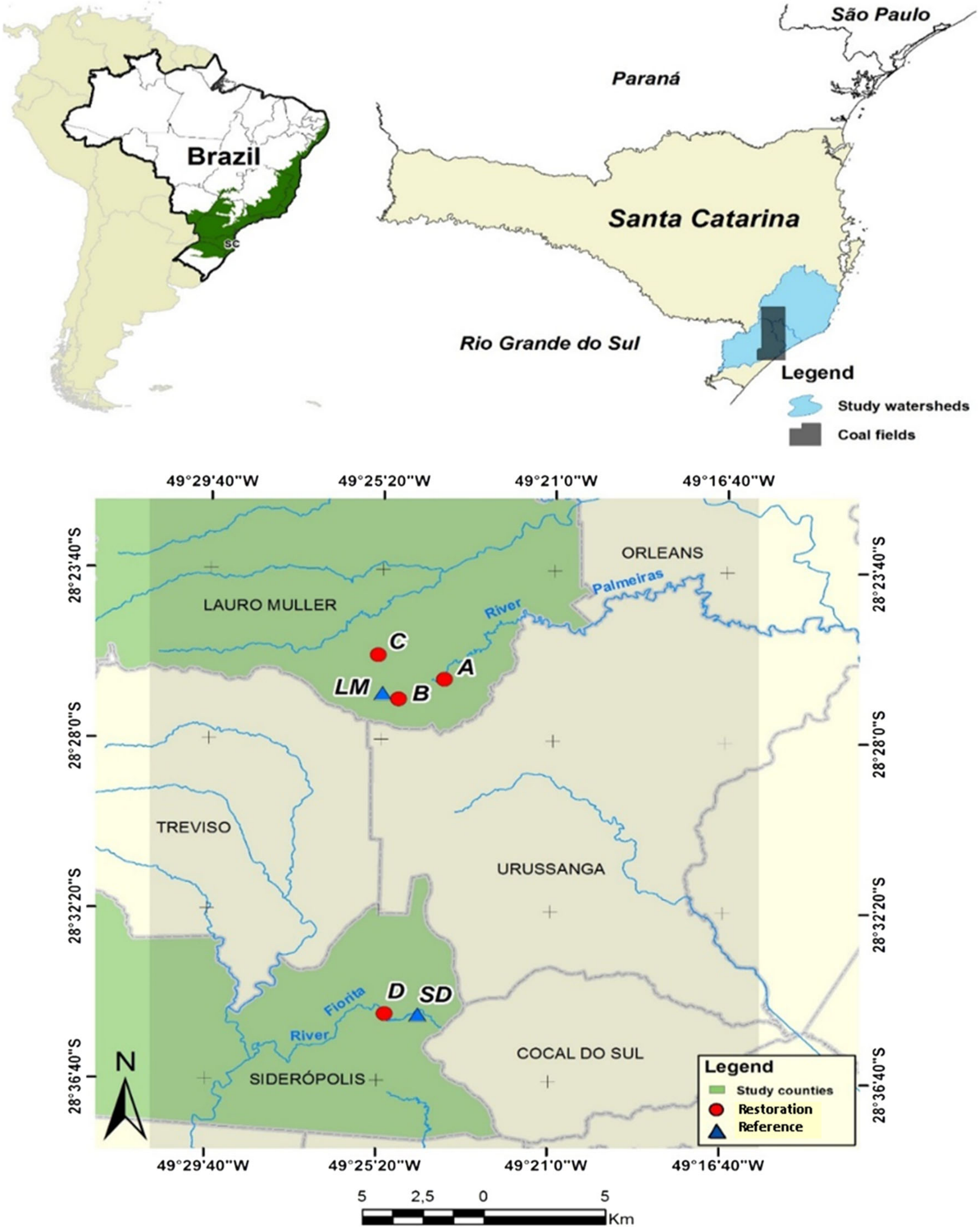

Fig. 1 Study area and location of four sites under ecological restoration and two reference areas, at southern Santa Catarina state

organic matter content (*OM*) by Walkley–Black method, and H + Al and Al^{3+} by NaOH titulometry. P, K and Na elements were extracted using a Mehlich^{-1} extractor and determined by flame photometry (K, Na) and colorimetric method (P). Calcium (Ca^{+2}) and magnesium (Mg^{+2}) were extracted using KCl^1 mol L^{-1} and measured using atomic absorption spectrophotometry.

Data analyses – To evaluate species composition, abundance and ecological traits of regenerating woody species in the four areas (Question 1), we did not perform any statistical analyses as we had no true replicates, but used descriptive and exploratory approaches. The number of individuals per species was standardized to density per 100 m^2. Here, we used data from the third evaluation for the areas under restoration and the single evaluation for reference areas.

For Question 2, we used four distinct matrixes, based on our 10 × 30 m plots: natural regeneration of woody species (species density by plot–response matrix), canopy structure (abundance, species richness and basal area based on both the planted trees and the spontaneously established individuals of the upper stratum), herbaceous cover (% of exotic grasses, of native grasses and of forbs) and chemical soil features.

To answer Question 2, we evaluated the proportion by which the distinct subsets of biotic and abiotic variables influenced regeneration patterns by partial redundancy analyses (RDAp) (Borcard et al. 2011). The response matrix was the natural woody regeneration stratum. Plots without any woody individuals were not considered; thus, we analyzed 29 (out of 32) samples units where a total of 46 species had been found. Explanatory matrices were soil chemistry (organic matter, Ca, H + Al, P and Ca + Mg/K) as abiotic variables, canopy structure (species abundance, richness and stem basal area) and herbaceous cover (% of exotic or native grasses and forbs) as biotic variables. The vegetation data were from the third evaluation and were Hellinger-transformed (Legendre and Gallagher 2001).

Before RDAp procedures, we evaluated the global significance of the model for each original explanatory matrix; based on this, only the soil chemistry and canopy structure matrices were considered for the following analyses. The matrices were submitted to forward selection procedures to identify the most important subset of variables explaining variance of the response matrix, using the BIOENV function and considering $p < 0.01$ after 999 randomizations (Blanchet et al. 2008). RDAp analyses were done using the package vegan (Vegan: Community ecology package) on the R platform (R Development Core Team 2009), and we considered the adjusted R^2 values (Peres-Neto et al. 2006).

To complement the second question, we visualized patterns of natural woody species regeneration at the different restoration sites by help of a principal coordinate analyses (PCoA), using the data used as response matrix in the RDAp. These analyses were carried out by MULTIV software (Pillar 2007). Data were previously standardized and centralized within variables, and chord distance was used as similarity measure. In the PCoA plot, we included biotic and/or abiotic variables that were significant in explaining natural regeneration in the areas (evidenced by RDAp results), accordingly to their correlation with both ordination axes.

The temporal dynamics of natural regeneration (Question 3) were also analyzed by principal coordinate analysis (PCoA), using abundance data of the woody regeneration stratum together with data on the herbaceous cover. Data were previously standardized and centralized within variables. Chord distance between sampling units was used as similarity measure. This analysis was done independently for each study site in order to respect the particularities of each area, avoiding statistical comparisons between ongoing restoration areas and aiming at identifying successional trajectories. Ordination analyses were carried out by MULTIV software.

3 Results

Species composition, abundance and ecological traits of regenerating woody species – Altogether, 47 woody species that had spontaneously established in areas under restoration were detected in the third evaluation of the regenerating woody stratum (Table 1), and 105 species were found in the lower woody stratum at the two reference sites (Online Resource 1). Considerable differences concerning richness, abundance and ecological traits, such as dispersal syndrome and successional stage, were found among areas (Table 2). In area B, only five species were recorded (total abundance of 0.61 ind. 100 m^{-2}), while in area D, 37 species were found and total abundance was much higher (17.78 ind. 100 m^{-2}). Only nine species were shared between restoration sites and reference areas: *Boehmeria caudata* Sw., *Casearia sylvestris* Sw., *Euterpe edulis* Mart., *Inga marginata* Kunth, *Matayba guianensis* Aubl., *Miconia cabucu* Hoehne, *Miconia sellowiana* Naudin, *Piper aduncum* L. and *Zanthoxylum rhoifolium* Lam.

Area D was the only one that showed an upper stratum (DBH ≥ 5 cm), with 14 species and a total abundance of 11 ind. 100 m ^{2} (Online Resource 2). In contrast, the reference areas presented 123 species (abundance 20 ind. 100 m^{-2}) in this stratum (Online Resource 1). Only three species were shared with area D (*Alchornea triplinernia* (Spreng.) Müll. Arg., *Annona rugulosa* (Schltdl.) H. Rainer and *Cecropia glaziovii* Snethl.).

All areas presented high cover of exotic grasses, especially areas A and B with 75 and 63% of mean cover, respectively (Table 3). The noninvasive annual grasses *Avena* and *Lolium* had disappeared completely in the areas where they were sown, while the two invasive species that had been introduced presented high cover values. In all areas, invasive grasses of the genus *Urochloa* showed high cover values.

Influence of abiotic and biotic variables on natural regeneration – In pRDA, two subsets of explanatory variables (soil chemistry and canopy structure; herbaceous cover was not was significant) were chosen to explain the pattern of occurrence and abundances of woody species in the regeneration stratum. (Table 3 summarizes the value for

Table 1 Species of the regenerating woody species recorded in areas in process of ecological restoration, considering the last evaluation (areas A, B and C: 4 years after initial intervention; and area D: 9 years after initial intervention) and given in abundance per area (individuals per 100 m^2)

Family/*species*	Acronym	Abundance (100 m^2)			
		A	B	C	D
Anacardiaceae					
Schinus terebinthifolius Raddi	Scte	0.00	0.00	0.10	1.28
Annonaceae					
Annona rugulosa (Schltdl.) H. Rainer	Anru	0.00	0.00	0.00	0.44
Arecaceae					
Archontophoenix cunninghamiana H. Wendl. & Drude	Arcu	0.00	0.00	0.00	0.11
Euterpe edulis Mart.	Eued	0.00	0.00	0.00	0.06
Asteraceae					
Austroeupatorium inulifolium (Kunth) R.M. King & H. Rob.	Auin	0.00	0.00	0.00	0.33
Baccharis vulneraria Baker	Batr	0.03	0.00	0.03	0.00
Baccharis semiserrata DC.	Base	0.27	0.06	2.57	0.00
Kaunia rufescens (Lund ex DC.) R.M. King	Karu	0.00	0.11	2.00	0.83
Piptocarpha axillaris (Less.) Baker	Pito	0.03	0.00	0.70	0.00
Senecio brasiliensis (Spreng.) Less.	Sebr	0.73	0.00	0.00	0.00
Vernonanthura discolor (Spreng.) H. Rob.	Vedi	0.00	0.06	0.00	0.06
Vernonanthura tweediana (Baker) H. Rob.	Vetw	0.13	0.00	0.43	0.06
Vernonanthura sp.	Vesp	0.00	0.00	0.00	1.39
Cannabaceae					
Trema micrantha (L.) Blume	Trmi	0.03	0.00	0.00	0.11
Euphorbiaceae					
Alchornea glandulosa Poepp. & Endl.	Algl	0.00	0.00	0.00	0.11
Alchornea triplinervia (Spreng.) Müll. Arg.	Altr	0.00	0.00	0.00	0.94
Croton celtidifolius Baill.	Crce	0.47	0.33	0.00	0.67
Fabaceae					
Inga marginata Willd.	Inma	0.00	0.00	0.00	0.06
Mimosa bimucronata (DC.) Kuntze	Mibi	0.00	0.00	0.00	0.28
Mimosa scabrella Benth.	Misc	0.00	0.00	0.00	0.22
Senna sp. (Vogel) H.S. Irwin & Barneby	Sen	0.00	0.00	0.03	0.00
Lamiaceae					
Aegiphila integrifolia (Jacq.) Moldenke	Aese	0.03	0.00	0.00	0.00
Lauraceae					
Ocotea puberula (Rich.) Nees	Ocpu	0.00	0.00	0.00	0.06
Melastomataceae					
Leandra australis (Cham.) Cogn.	Leau	0.00	0.00	0.00	0.39
Miconia cabucu Hoehne	Mica	0.00	0.00	0.00	0.33
Miconia ligustroides (DC.) Naudin	Mili	0.00	0.00	0.00	0.06
Miconia sellowiana Naudin	Mise	0.00	0.00	0.00	0.39
Myrtaceae					
Psidium guajava L.	Psgu	0.00	0.00	0.00	0.11
Nyctaginaceae					
Pisonia zapallo Griseb.	Piza	0.00	0.00	0.00	0.06
Oleaceae					
Ligustrum lucidum W.T. Aiton	Lilu	0.00	0.00	0.00	0.06
Piperaceae					
Piper aduncum L.	Piad	0.00	0.00	0.00	1.67
Piper arboreum Aubl.	Piar	0.00	0.00	0.00	0.06

Table 1 (continued)

Family/*species*	Acronym	Abundance (100 m^2)			
		A	B	C	D
Primulaceae					
Myrsine coriacea (Sw.) R.Br. ex Roem. & Schult.	Myco	0.23	0.00	0.10	5.39
Rosaceae					
Rubus rosifolius Sm.	Ruro	0.00	0.00	0.00	0.28
Rutaceae					
Citrus sp.	Citrus	0.00	0.00	0.03	0.00
Zanthoxylum rhoifolium Lam.	Zarh	0.00	0.00	0.00	0.06
Salicaceae					
Casearia sylvestris Sw.	Casi	0.00	0.00	0.00	0.11
Sapindaceae					
Cupania vernalis Cambess	Cuve	0.00	0.00	0.00	0.06
Matayba guianensis Aubl.	Magu	0.00	0.00	0.00	0.11
Solanaceae					
Solanum americanum Mill.	Soam	0.00	0.00	0.03	0.28
Solanum mauritianum Scop.	Soma	0.13	0.00	0.47	0.00
Solanum pseudocapsicum L.	Sops	0.00	0.00	0.10	0.11
Solanum reflexum Dunal	Sore	0.00	0.00	0.13	0.00
Solanum variabile Mart.	Sova	0.50	0.00	0.40	0.44
Urticaceae					
Boehmeria caudata Sw.	Boca	0.07	0.06	0.03	0.00
Boehmeria macrophylla Hornem	Boma	0.00	0.00	0.00	0.72
Cecropia glaziovii Snethl.	Cegl	0.00	0.00	0.00	0.11
Abundance total (individuals 100 m^{-2})		2.67	0.61	7.17	17.78

The acronyms indicated are used in the figures

each selected variable.) The analysis explained 24% of the variation of the response matrix (Fig. 2).

Ordination of the full set of plots described by spontaneously established woody species showed clear overall differences among the four areas (Fig. 3). Plots of area D were separated from the other plots among the first axis and plots of area C among the second. Plots of areas A and B were situated closely together and clearly were characterized by the low regeneration of woody species in the lower stratum, contrasting with plots from areas C and D. Plots of area D were positively related to the density of woody individuals and to tree basal area. Plots of areas C were highly associated with the two pioneer shrubs *Baccharis semiserrata* and *Kaunia rufescens* R.M. King & H. Rob.

Table 2 Ecological traits of woody species sampled in the regeneration stratum at the restoration sites (A, B, C and D), considering the last evaluation (areas A, B and C: 4 years after initial intervention; area D: 9 years after initial intervention) and at remnant forests (average of values recorded at the two reference areas)

Ecological traits	Area A		Area B		Area C		Area D		Remnant forests	
	Sp.	Ind.	Sp.	Ind.	Sp.	Ind.	Sp.	Ind.	Sp.	Ind.
Number/100 m^2	1.6	10.6	0.6	1.5	2	28.6	4.9	42.6	10.3	22.8
(Absolute)	(12)	(80)	(5)	(11)	(15)	(215)	(37)	(320)	(77)	(684)
Anemochory (%)	41.7	46.3	80.0	45.5	33.3	80.0	10.8	13.1	3.7	1.7
Autochory (%)	0.0	0.0	0.0	0.0	6.7	0.5	8.1	3.1	8.6	8.8
Zoochory (%)	41.7	33.8	20.0	54.5	46.7	13.5	70.3	75.0	85.6	89.2
Non-pioneer species (%)	0.0	0.0	0.0	0.0	0.0	0.0	18.9	6.3	83.9	92.3
Pioneer species (%)	83.3	80.0	100	100	80.0	93.5	67.6	87.8	14.1	7.4
Exotic (%)	0.0	0.0	0.0	0.0	0.0	0.0	8.1	2.8	0	0

Table 3 Set of matrices with variables considered for the partial RDA analysis. Only significant variables of each predictive matrix are presented ($P < 0.05$)

Set of matrices/variables	Area A	Area B	Area C	Area D
Categories of herbs (% of cover)				
Exotic grasses	75.48 ± 7.73	63.64 ± 1.10	46.67 ± 20.68	42.43 ± 20.54
Native grasses	5.28 ± 5.51	6.31 ± 3.36	12.86 ± 9.38	5.46 ± 3.92
Forbs	24.19 ± 10.00	6.92 ± 3.58	41.03 ± 14.02	50.63 ± 20.35
Soil chemistry				
Organic matter (OM, %)	15.50 ± 7.08	15.09 ± 2.50	16.64 ± 3.24	8.66 ± 2.49
Calcium (Ca, cmolc dm^{-3})	19.56 ± 3.76	9.46 ± 0.61	12.80 ± 3.49	7.48 ± 2.15
H + Al (cmolc dm^{-3})	13.67 ± 9.95	22.98 ± 7.94	9.84 ± 2.79	8.80 ± 5.67
Phosphorus (P, mg dm^{-3})	304.26 ± 53.23	231.21 ± 48.86	328.12 ± 11.52	51.36 ± 20.22
Relation of Ca + Mg/K	26.72 ± 6.90	21.47 ± 2.90	24.88 ± 8.27	48.93 ± 14.39
Canopy structure (upper stratum + planted trees)				
Richness (sp./100 m^2)	0.06 ± 0.08	0.06 ± 0.03	0.14 ± 0.11	0.43 ± 0.07
Density (ind./100 m^2)	22.55 ± 14.89	29.75 ± 9.14	45.10 ± 13.51	38.33 ± 13.17
Basal area (m^2/100 m^2)	10 ± 5.27	16.75 ± 1.71	15.20 ± 5.24	7.17 ± 3.06

Given are mean values and standard deviation (± SD) per area under ecological restoration

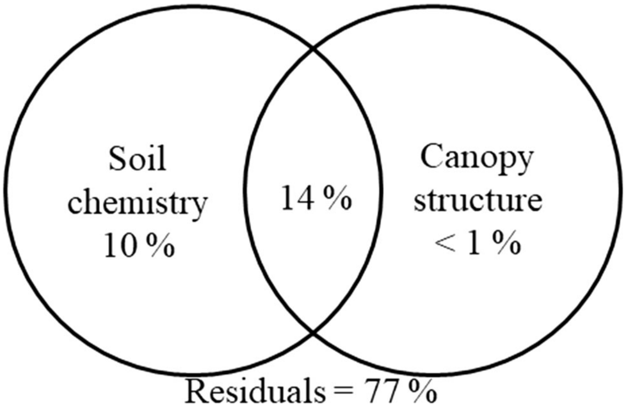

Fig. 2 Groups of variables explaining woody species regeneration at four restoration sites degraded by mining in Santa Catarina, southern Brazil. Given are adjusted R^2 values of subsets of variables significantly related to the response matrix (see Table 3), as found by RDAp analysis

Areas differed not only in terms of vegetation, but also in soil features, as seen by the association of areas A and B to high values of P, Ca^{+2} and H + Al in the constructed soil.

Regenerating dynamics of woody species – The regenerative layer of woody species, evaluated together with the cover categories of the herb layer, showed, in all areas, high dynamics in terms of species composition and abundance over the 3 years of monitoring (Fig. 4). From the first to the third evaluation, most plots shifted completely their position in the diagram. Exotic grasses, especially in areas A, B and C, markedly dominated plots in the first evaluation. In the third evaluation, the regeneration of woody species became stronger in all areas, indicating that a large number of species arrived and/or increased in abundance.

4 Discussion

Our analysis of four restoration sites with a history of severe degradation by coal mining and that since then had been subjected to strong restoration interventions—complete reconstruction of the substrate and subsequent introduction of vegetation—evidenced distinct vegetation recovery among areas. Survival of planted trees, number of regenerating tree species and cover of invasive grasses varied considerably, and soil chemical features and canopy cover were identified as the principal drivers for the differences found among areas.

Highly impacted lands need a considerable time to allow the establishment of natural regeneration processes (Liu et al. 2011; Zipper et al. 2011; Zhenqi et al. 2012), and that areas as those studied by us still differ considerably from the reference areas thus is not surprising. The ecological traits of the woody species found in the regeneration stratum at the restoration sites were indicative of a very early succession stage of woody vegetation, as shown by the high percentage of wind-dispersed and of pioneer species. Area D, the area with the longest time since initiation of restoration, was somewhat more similar to reference sites, despite still very considerable differences in species richness and composition. Clearly, our sites are in early successional phases, and similarity (or lack of similarity) with reference areas in regard to species composition and abundance is no adequate indicator for restoration success

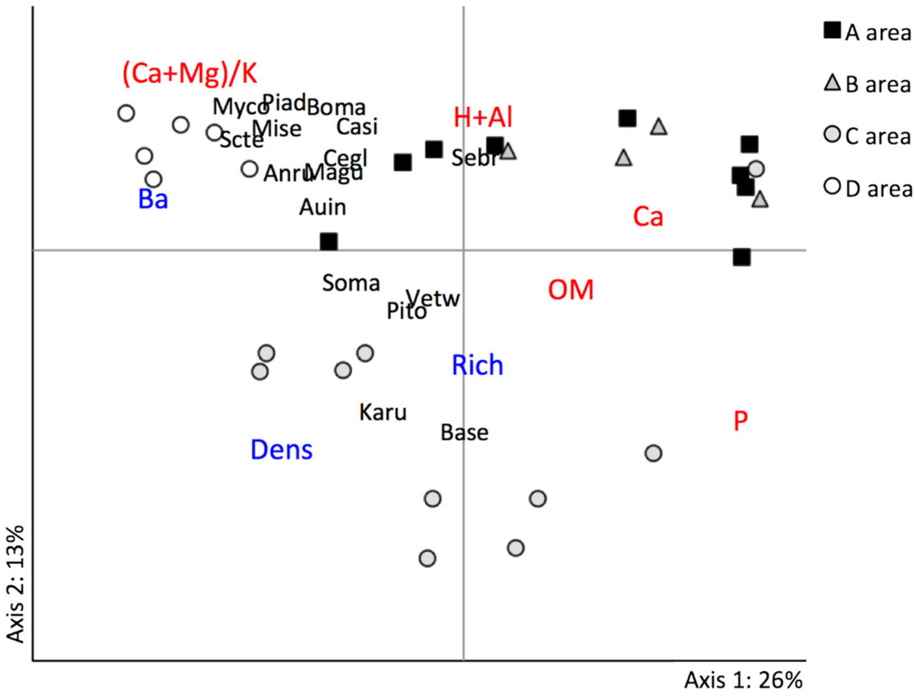

Fig. 3 Principal coordinates ordination diagram of plots with woody species regeneration at four restoration sites degraded by mining in Santa Catarina, southern Brazil. Plots are described by species abundance. Species with highest correlation to the ordination axis are plotted in the diagram (see labels in Table 1). Additionally, abiotic (red font—soil chemistry—Ca: calcium; H + Al: potential acidity; P: phosphorus; (Ca + Mg)/K: relation between that cations) and biotic variables (blue font—canopy structure—Ba: basal area; Dens: density; Rich: richness) were plotted according to their correlation with the axes

at the beginning of the restoration process (Martinez-Ramos and Soto-Castro 1993; Chazdon et al. 2007).

Nonetheless, the higher similarity of area D, with a longer time since the beginning of restoration, especially in the proportion of animal-dispersed and non-pioneer species, indicates that successional processes toward the reference systems have been initiated. Despite the strong degradation and the necessity for severe intervention such as soil construction, we thus can expect convergence of the other areas. This contrasts the opinion that restoration of areas with this kind of degradation is totally infeasible (Tozer et al. 2011).

The high variability in species composition and woody species abundances among sites seems to be determined both by chemical properties of the soil (abiotic component) and by the development of an upper vegetation stratum (biotic component). Our results also indicate the strong negative influence of exotic grasses on establishment of woody species individuals, as shown by other studies (Batten et al. 2005; Avio et al. 2013; Hui-na et al. 2014).

Plots with high content of phosphorus (P) were related to high abundance of grasses and to lower development of the planted trees, which resulted in low natural regeneration of woody species. This is probably a consequence of the way soil fertilization is commonly conducted in restoration projects in the region: Together with the seeding of exotic grasses to rapidly cover the soil, fertilization that follows the guidelines for agricultural systems is applied, favoring the development of the grass layer and favoring invasive grasses (Högberg 2007; Jung and Lal 2011; Calonego and Rosolem 2013; Fonte et al. 2014). Only little knowledge on nutritional requirements of native species is available for the region; one study on native species from our region has shown that higher P uptake leads to significantly higher growth only for few pioneer species (Pasqualini et al. 2007). A better understanding of the demands of native plants is important to guide soil construction and preparation in order to make ecological restoration more efficient.

The development of introduced trees positively influences natural regeneration (Parrotta et al. 1997b; Omeja et al. 2011), as seen in area D, with a canopy of the seeded *Mimosa scabrella*, a fast-growing pioneer. Canopy closure changes local conditions (e.g., microclimate), increases the potential for arrival of seeds (perches) and facilitates the establishment of native trees through the exclusion of invasive grasses by shading (Chazdon 2003; Lindenmayer et al. 2010; Nyamai et al. 2011; Omeja et al. 2011; Rodrigues et al. 2011). *Mimosa scabrella* is a legume species capable to fix nitrogen, which is of high relevance to improve degraded soil conditions (Lammel et al. 2013; Citadini-Zanette et al. 2017). The establishment and growth of the first introduced species thus crucially contribute to restoration success, triggering the further community development. These results and the importance of priority effects on community assembly processes (von Gillhaussen et al. 2014) appear to be important for the decision which species should best be selected for tree plantings or seeding in the restoration of highly degraded lands. While, on the one hand, the restoration aim may be

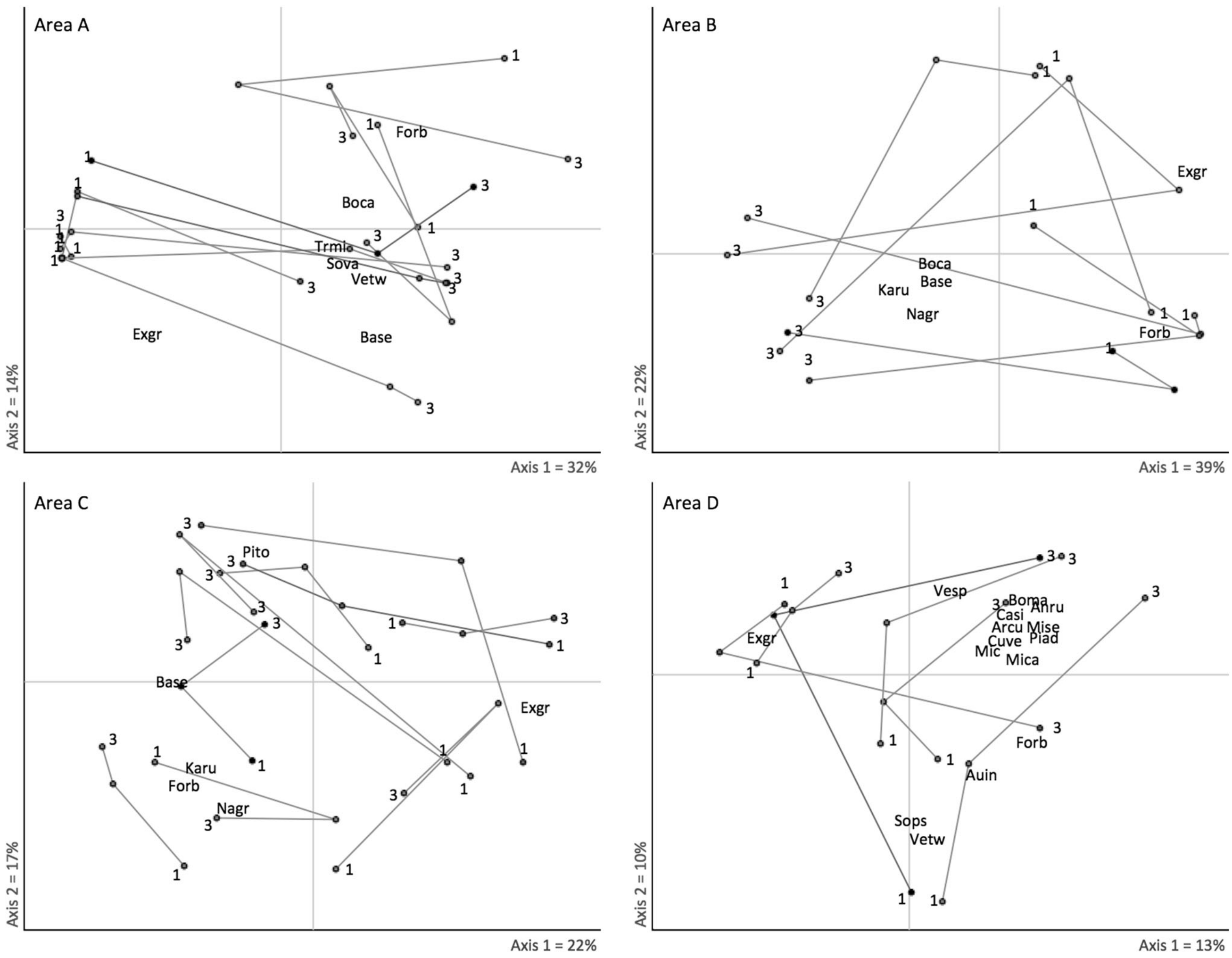

Fig. 4 Ordination diagram of the areas under ecological restoration (A, B, C and D) based on woody species of the regenerating stratum and on the proportion of herb categories (exotic grasses: Exgr; native grasses: Nagr; forbs: Forb), measured in three evaluations (A, B and C areas: 18, 30 and 40 months after tree planting; D area: 8, 9 and 10 years after tree planting). Each plot is connected through the time (from 1 to 3, the last evaluation). Species with highest correlation (> 0.5) are shown in the respective diagram (see labels in Table 1)

the high diversity of species (Rodrigues et al. 2011), the first restoration steps should aim at reestablishing vegetation structure and conditions that will enable community assembly processes without further strong or lasting human interventions (Parrotta et al. 1997b; Omeja et al. 2011). At the same time, it should be carefully analyzed which plants are able to survive under harsh environmental conditions, e.g., on completely reconstructed soils.

Altogether, the results from our study emphasize the necessity to establish realistic goals for each step or phase of a restoration project, and the first goal should be related to canopy closure (Parrotta et al. 1997b; Omeja et al. 2011) and improvement of substrate conditions. Under strongly constraining abiotic and biotic conditions, and with large distances from the reference state, the establishment of high species diversity is no adequate goal for early restoration phases, even though this might be the final goal (Failing et al. 2013). The perspective of restoration as a process implies that the evaluation of restoration success should consider initial, intermediate and final goals: This makes the entire restoration process more realistic. The analysis of trajectories over time seems important and should cover longer period. The fact that the woody species communities showed high dynamics within the 3 years period of monitoring, even in area D, the “oldest” of the restoration sites, emphasizes the need of monitoring, also to advance in theoretical questions in the field of community assembly. Longer monitoring also seems to be necessary in order to be able to infer if the plant communities will, in the future, converge with the reference community or not. The establishment of intermediate goals for ecological restoration thus is an important step that will also allow to plan adequate management interventions during the restoration process.

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Author Contributions ERN conceived and designed the research, performed the field work and the organization of the dataset, analyzed the data, wrote and edited the main part of the manuscript and obtained a grant from FAPESC (Fundação de Amparo à Pesquisa de Santa Catarina). MLC designed and supervised the field work related to soil analysis and interpreted soil data and contributed on soil–plants interactions, writing and reviewing the manuscript. GTC performed the field work and the organization of the dataset. GEO helped to design the research, analyzed the data and participated in writing and editing the manuscript. SCM helped to conceive and design the research, analyzed the data and participated in writing and editing the manuscript, and GEO and SCM received productivity grants from CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico).

Compliance with ethical standards

Conflict of interest We declare that there is no conflict of interest.

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