FLORISTIC AND EDAPHIC INVENTORY OF ATLANTIC RIPARIAN FORESTS: REFERENCES FOR RESTORATION PROJECTS

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The use of reference ecosystem inventories to guide ecological restoration is essential for monitoring the success of environmental recovery. The aim of this study was to carry out a floristic and edaphic inventory in old growth riparian forest remnants from the upper River Doce watershed, to provide subsidies for restoration programmes. The study was carried out in the municipalities of Rio Casca, Sem-Peixe, and Santa Cruz do Escalvado. The most representative families in species richness were Fabaceae, Meliaceae, Sapindaceae, Bignoniaceae, and Salicaceae. Based on the chemical properties of the soils, there was considerable heterogeneity among plots, with soils ranging from acidic to neutral (pH 3.8–6.3), with variable contents of phosphorus (0.0–7.6 mg × dm^{-3}), and aluminum saturation (0.0–66.5%), among other factors. The co-inertia analysis showed a highly significant connection of 51.5% ($p < 0.001$) between floristic and edaphic matrices in tree stratum, and 46.5% ($p < 0.001$) between floristic and edaphic matrices in the sapling stratum. The reference ecosystems presented here suggest that action plans aimed at recovering the riparian forest should consider the edaphic conditions and its relationship with the plant community on a regional scale, avoiding the extrapolation of observed pattern of taxon-environment relationships to other regions.

Key words: River Doce watershed, plant community, reference ecosystem, Samarco dam breach, soil-vegetation relationship

Introduction

Tropical forests are considered a source of biological diversity, harbouring approximately two-third of all biodiversity on Earth (Shimamoto et al., 2018). One of the most diverse forests in the Tropics is the Brazilian Atlantic Forest, which consists of various ecosystem types (Mittermeier et al., 2011; Neves et al., 2017; Esser et al., 2019; Marques & Grelle 2021). The Atlantic Forest is included on the list of world hotspots due to alarming levels of habitat loss (Esser et al., 2019). The Atlantic Forest once covered an area of 1 315 460 km^2, but currently only ca. 12.4% of its original area remains preserved as scattered fragments, mostly with areas smaller than 0.5 km^2 (Ribeiro et al., 2009; Marques & Grelle, 2021).

Among the main agents of degradation of the Atlantic Forest, the agriculture stands out. On large rural properties pastures and crops have led to high levels of deforestation, while mining represents intense levels degradation (Guerra et al., 2020). The high deforestation rates have resulted in the loss of regenerative capacity of these forests, and drastic loss of ecosystem services (Gardner et al., 2009; Ferraz et al., 2014; Shimamoto et al., 2018).

One of the main objectives of restoration is the recovery of ecosystem features that have been lost or degraded, thus creating and establishing reference ecosystems are an extremely important task (Fernandes et al., 2016b; Gann et al., 2019). A reference ecosystem is an ecosystem that serves as a guide (control) for restoration projects, as well as for monitoring the success of national, regional and local restoration plannings (Gann et al., 2019). Restoration projects must provide bases for recovered environments to replicate the features of reference ecosystems (Goebel, 2005; Toma et al., 2023). Studies on floristic composition, vegetation structure, and soil characterisation are important for identifying endangered species and for characterising aspects of local ecology, essential for creating reference ecosystems aimed at recovering degraded areas (Coelho et al., 2018; Fagundes et al., 2019; Toma et al., 2023). This information favours management actions in land use and occupation, especially in hydrographic basins (Uniyal et al., 2020).

The riparian forest is a system that is changing over time due to the influence of natural factors, disasters, and, mainly, various land uses (Fagundes et al., 2019; Riis et al., 2020). In this context, the environmental disaster in the River Doce watershed caused by the rupture of the Fundão dam, in the municipality of Mariana (Brazil), released tailings with high concentrations of heavy metals and caused the loss of approximately 90% of the riparian vegetation of the River Fundão, River Gualaxo do Norte and River Carmelo in 2015 (Fernandes et al., 2016a; Omachi et al., 2018). This acute environmental impact on the Atlantic Forest caused the loss of its regenerative capacity by compromising its local «ecological memory» (Fernandes et al., 2016a). Furthermore, the Atlantic Forest of the River Doce watershed has been suffering long historical degradation of the landscape due to changes in soil use and occupation (Oliveira et al., 2020; Fraga et al., 2021). Examples of remnants that could be used as reference ecosystems are scattered in the landscape with few fragments of natural formations remaining in intermediate and late stages of regeneration (Ribeiro et al., 2009). The recovery of degraded areas in these territories requires the adoption of active restoration methodologies, such as planting seeds and/or seedlings (Rodrigues et al., 2009) that could in turn facilitate the successional process (e.g. Spadeto et al., 2017) and impact positively the higher trophic levels (Li et al., 2023). Hence, understanding the vegetation along the river must be accomplished, if proper ecological restoration is our main goal.

Understanding the relationships between vegetation structure and edaphic factors is essential for the adoption of restoration strategies linked to the particularities of each area (Fagundes et al., 2019; Rozendaal et al., 2019; Figueiredo et al., 2022; van der Sande et al., 2023). In this way, the objective of this study was to carry out a floristic, phytosociological, and edaphic inventory in riparian forest remnants of the upper River Doce watershed, to provide information that would help in the composition of a reference ecosystem and provide subsidies for recovery projects of the areas affected by the rupture of the dam.

Material and Methods

Study area

In the present study, we selected three riparian forest sample sites (Fig. S1) located in the upper River Doce watershed, Minas Gerais, southeastern Brazil (Fig. 1). The sample sites were at least 3 km distant from each other. These are site 1: Rio Casca municipality, Jurumirim district (20.053250° S, 42.761056° W); site 2: Sem-Peixe municipality, São Bartolomeu de Sem-Peixe district (20.008083° S, 42.767028° W); site 3: Santa Cruz do Escalvado municipality, Zito Soares district (20.135167° S, 42.759111° W). The dominant vegetation type in the study area is the Atlantic Forest (Neves et al., 2017; Esser et al., 2019). The regional climate in Rio Casca and Sem-Peixe municipalities is classified as Aw (tropical climate), and in Santa Cruz do Escalvado as Cwa (humid subtropical climate), according to the Köppen classification (Alvares et al., 2013). In Rio Casca, Sem-Peixe, and Santa Cruz do Escalvado municipalities, the average temperature is ca. 21.3°C, and the annual precipitation is ca. 1452 mm (Alvares et al., 2013).

Sampling and phytosociological parameters

We used the sampling method of fixed area plots (Mueller-Dombois & Ellenberg, 1974) for the phytosociological survey. The parameters calculated for the vegetation structure were the absolute and relative values of density (number of individuals), dominance (based on basal area), frequency (number of occurrence plots), and importance value (IV) (Mueller-Dombois & Ellenberg, 1974). For the phytosociological survey of the tree stratum, we marked 15 plots of 10 × 10 m (100 m^2) on each sample site. We systematically allocated the plots from the riverbank to the interior of the forest, with a minimum distance of 10 m between plots. Within each plot we quantified all woody individuals with DBH (diameter at breast height = 1.30 m from the ground) > 5 cm. We marked the sampled individuals with numbered aluminum plates. For the phytosociological survey of the sapling stratum, we marked one sub-plot of 5 × 5 m (25 m^2) in the corner near the riverbank of each 100 m^2 plot. We registered within each sub-plot all herbaceous and shrubby individuals with diameter at ground height ≥ 1 cm and ≤ 5 cm with the aid of a digital caliper. We marked the sampled individuals with numbered aluminum plates. After that, we collected the branches from all individuals for taxonomical identification.

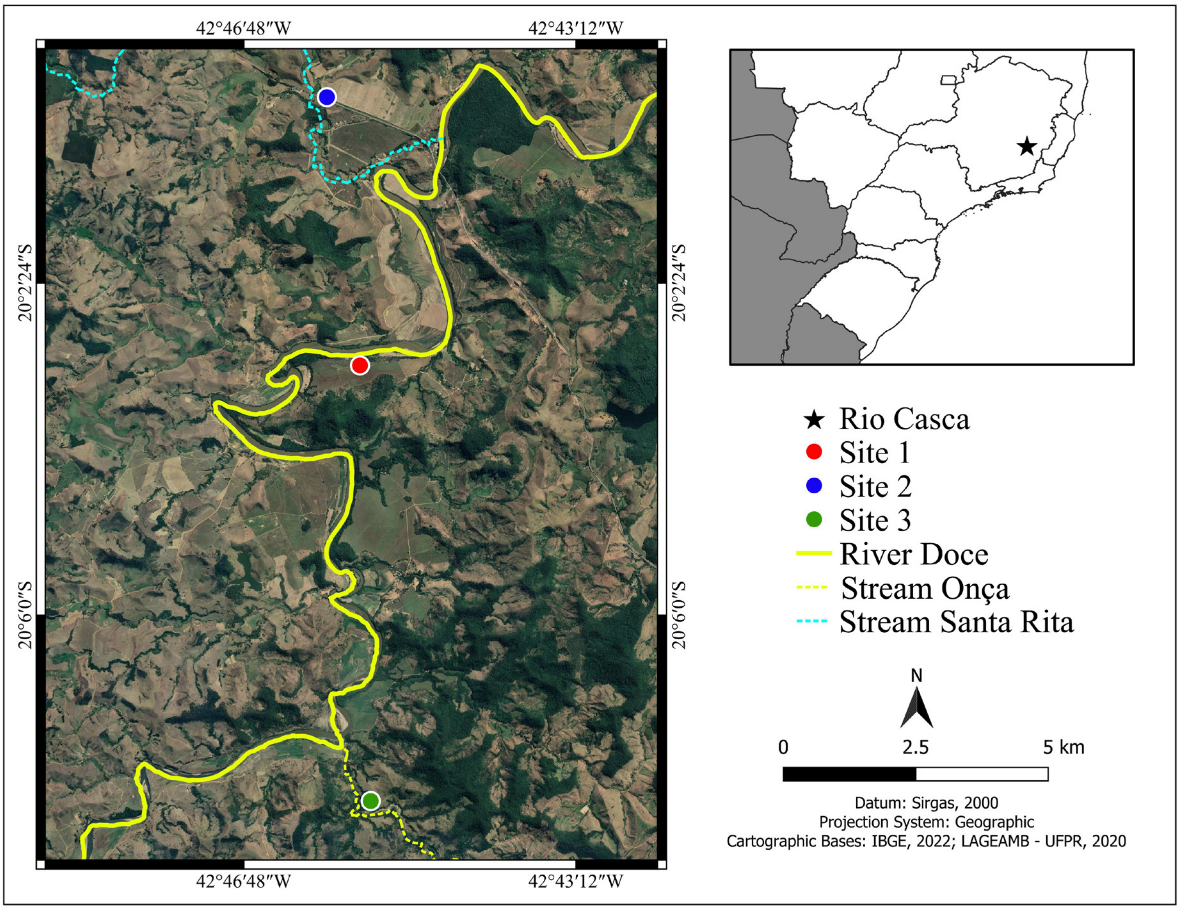

Fig. 1. The location of the three sampling sites in riparian forests at the upper River Doce watershed, southeastern Brazil. Designations: site 1 – Rio Casca municipality, site 2 – Sem-Peixe municipality, site 3 – Santa Cruz do Escalvado municipality.

We collected herbarium specimens from each individual in the tree and sapling stratum for taxonomic identification. We deposited all identified specimens in the Montes Claros Herbarium (MCMG) at State University of Montes Claros (Unimontes). The identification of the collected botanical material was carried out through consultation with specialists and comparisons with existing specimens in the herbarium. We used the Angiosperm Phylogeny Group IV system (APG IV, 2016) for the classification of species into families. Synonymy verification, nomenclature and species authors were obtained through the «WorldFlora» package (Kindt, 2020) in the R environment (R Core Team, 2018), standardised according to World Flora Online (WFO; http://www.worldflora-online.org/). We made additional checks through the Flora e Funga do Brasil (2022) for species not found in WFO.

Soil sampling

We collected five soil samples of 100 g each at 20 cm deep per plot. Four samples were collected at the corners and one at the centre of the plot. The five samples were mixed *in situ* and transformed into a composite sample per plot. Each composite sample represented a valid estimate of the mean edaphic parameters for the plot (Binkley & Vitousek, 1989). The chemical and granulometric analysis of the soil samples were made by the Soil Department of the Federal University of Viçosa (UFV). Textural analyses were done according to Donagemma et al. (2017) and chemical analyses followed Silva et al. (1999). The base saturation and aluminum saturation were calculated, respectively as follows: Base saturation = 100 $(K + Ca^{2+} + Mg^{2+})/(K + Ca^{2+} + Mg^{2+} + H{+}Al)$; Aluminum saturation = 100 $Al/(K + Ca^{2+} + Mg^{2+} + Al^{3+})$.

Statistical analysis

To assess the sample completeness, we constructed rarefaction curves for species diversity using the function «rare_Rao» from package «adiv» (Pavoine, 2020) following Ricotta et al. (2012), in which expected species diversity for each sampling site was computed as a function of the cumulative number of plots. We used the resampling approach with 10 000 iterations. We evaluated the pattern of exclusive and shared species among the three studied sites through Venn diagrams constructed for both tree and sapling strata using the package «VennDiagram» (Chen & Boutros, 2011).

To determine the relationship between soil parameters and the plant species community, we performed a co-inertia analysis (COIA). This robust and flexible analysis measures the agreement between two multivariate data sets, also called co-structure (Dolédec & Chessel, 1994; Dray et al., 2003). We performed the COIA for the tree and sapling strata separately. The edaphic matrix was constructed with the values of 19 soil parameters from the 45 plots (15 per site), while the floristic matrix was constructed with data of the incidence (presence and absence) of plant species in the tree and sapling strata from the 45 plots. The COIA output is a RV coefficient, which measures the strength of the association between the two matrices. The RV coefficient is bounded to 0 (i.e. no association) and 1 (i.e. maximum association). The significance (p-value) of the RV coefficient was defined by Monte Carlo permutation, performed with 10 000 randomisations. To perform the COIA, a Principal Components Analysis (PCA; mean = 0; standard deviation = 1) was used for the soil matrix, and a centered PCA (mean = 0) was used for each floristic matrix, according to Dray et al. (2003). To attain the assumptions of normality in the distribution of errors for statistical analyses, we performed square root transformation for phosphorus (P), potassium (K), copper (Cu), manganese (Mn), iron (Fe), and silt data, and logarithmic transformation for calcium (Ca), magnesium (Mg), aluminum (Al), zinc (Zn), Al saturation, and fine sand. To access the association between each soil parameter and COIA axis 1, we performed a Pearson's correlation between soil values and plot co-ordinates on COIA axis 1. We defined the association between species and the COIA axis 1 by the species co-ordinates on axis 1. We performed COIA using the «ade4» package (Dray & Dufour, 2007). We did all analyses in the R environment (R Core Team, 2018).

Results

In this study we found 145 plant species belonging to 35 families, being 87 species of 27 families in the tree stratum (Table S1), and 88 species of 30 families in the sapling stratum (Table S2). The rarefaction curves approximate to stabilisation for the three sites and for both, tree (Fig. 2a,b,c) and sapling strata (Fig. 2d,e,f). It indicates a completeness sampling of species diversity.

In the tree stratum, the richest family was Fabaceae (11 species), followed by Meliaceae (six species), Sapindaceae (four species), and Bignoniaceae (four species). Seventeen families were represented by only one species (Table S1). Regarding the importance value (IV), Meliaceae accounted for 26.0%, followed by Fabaceae (25.4%), Apocynaceae (4.2%), and Moraceae (3.3%) (Table S1). The most important tree species was *Guarea macrophylla* Vahl (Meliaceae; IV: 18.6%), followed by *Anadenanthera colubrina* (Vell.) Brenan (Fabaceae; 16.8%), *Trichilia pallida* Sw. (Meliaceae; 3.8%), and *Tabernaemontana solanifolia* A.DC. (Apocynaceae; 3.6%) (Table S1). In the tree stratum, we registered 32 undetermined species and they accounted for 14.9% of the IV.

In the sapling stratum, the richest families were Fabaceae (13 species), followed by Meliaceae (eight species), Salicaceae (four species), Moraceae (three species), and Rutaceae (three species). Fourteen families were represented by only one species (Table S2). Regarding the importance value (IV), Erythroxylaceae accounted for 14.6% of IV, followed by Piperaceae (12.4%), Anacardiaceae (9.1%), and Meliaceae (8.1%) (Table S2). The most important sapling species was *Erythroxylum pelleterianum* A.St.-Hil. (Erythroxylaceae; IV: 13.1%), followed by *Piper arboreum* Aubl. (Piperaceae; 10.7%), *Siparuna guianensis* Aubl. (Siparunaceae; 5.6%), and *Astronium graveolens* Jacq. (Anacardiaceae; 5.4%) (Table S2). In the sapling stratum we registered 21 undetermined species and they accounted for 9.4% of IV.

Two species from the tree stratum occurred on the three studied sites, *Anadenanthera colubrina* and *Guarea macrophylla* (Fig. 3a), which also were the two most abundant species in this stratum (Table S1). However, most species were exclusive for each site. The number of exclusive species in tree stratum of sites 1, 2, and 3 were, 23 (74%), 38 (76%), and 15 (60%), respectively (Fig. 3a). Regarding the sapling stratum, five species occurred on all the three studied sites, *Allophylus racemosus* Sw. (Sapindaceae), *Astronium graveolens*, *Casearia sylvestris* Sw. (Salicaceae), *Erythroxylum citrifolium* A.St.-Hil., and *E. pelleterianum* (Erythroxylaceae) (Fig. 3b). Among these species, only *Erythroxylum pelleterianum* and *Astronium graveolens* stand out among the ten species with the highest IV in the sapling stratum (Table S2). Similar to the tree stratum, the majority of sapling species were exclusive for each site. The number of exclusive sapling species in sites 1, 2 and 3 were 14 (53.8%), 47 (75.8%), and 10 (45.5%) respectively (Fig. 3b).

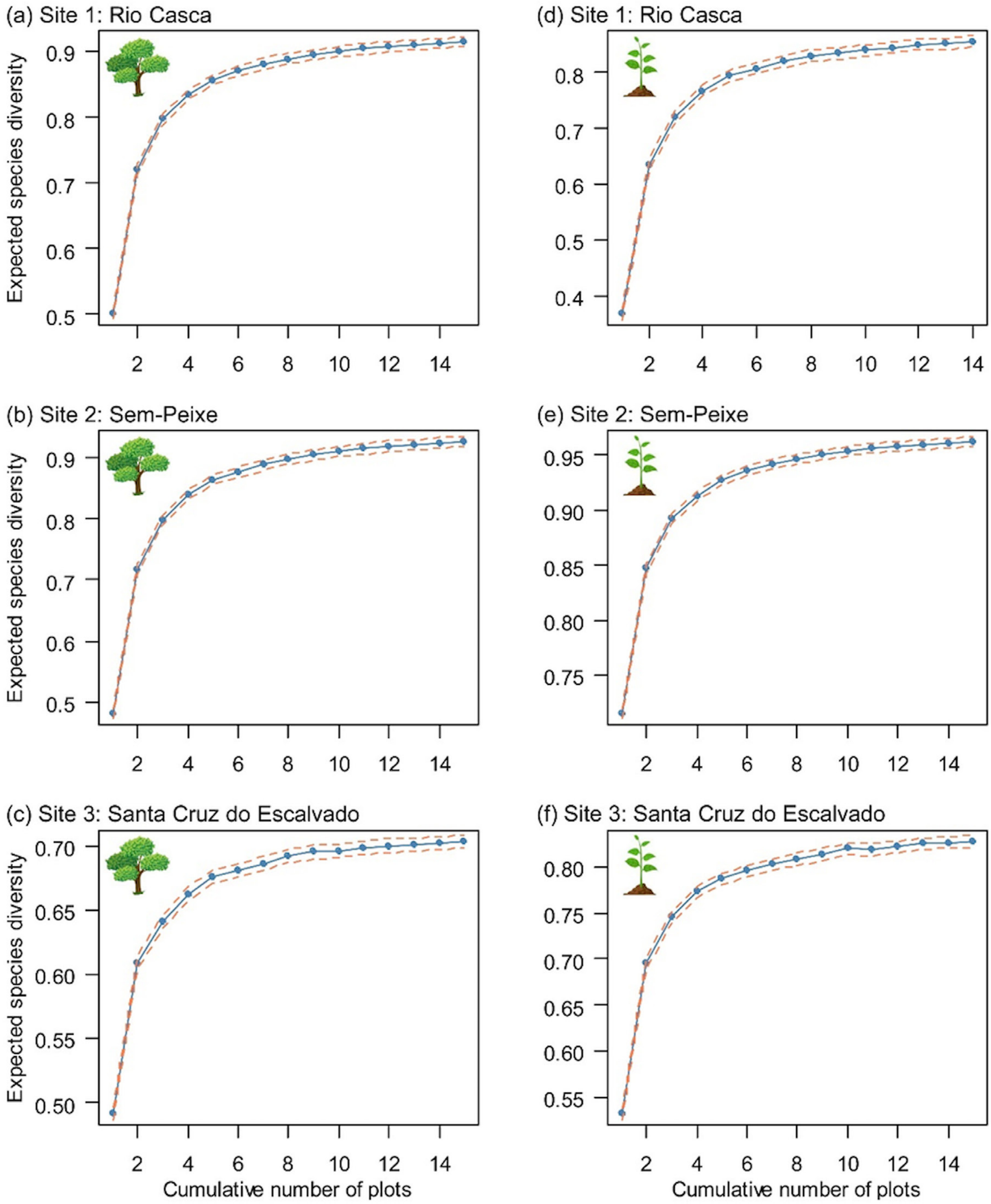

Fig. 2. Rarefaction curves for species diversity (Gini-Simpson index) as a function of sampling effort (cumulative number of plots). Designations: tree stratum at site 1 (a), site 2 (b), and site 3 (c); sapling stratum at site 1 (d), site 2 (e), and site 3 (f). Blue dots and continuous line indicate the expected species diversity. Red dashed line indicates the 95% confidence interval.

The edaphic factors showed a wide variation, indicating a considerable heterogeneity among plots and sites (Table 1). Based on the chemical properties of the sampled soils, the pH was on average acidic, ranging from 3.83 to 6.30, with 78% of the plots with acidic soils (pH < 5.5). The concentration of phosphorus ranged from 0.0 mg × dm^{-3} to 7.6 mg × dm^{-3}, the base saturation ranged from 9.9% (nutritionally poor soil) to 82.5% (nutritionally rich soil), while the aluminum saturation ranged from 0.0% to 66.5%. Some micronutrients showed a wide variation, like manganese and iron, ranging from 9.1 mg × dm^{-3} to 215.5 mg × dm^{-3} and 14.8 mg × dm^{-3} to 239.8 mg × dm^{-3}, respectively. Regarding the soil texture, there was also a wide variation among the sampling plots (Table 1). The coarse sand proportion ranged from 10.7% to 79.0%, the silt ranged from 2.7% to 28.5%, and the clay ranged from 6.9% to 52.9%.

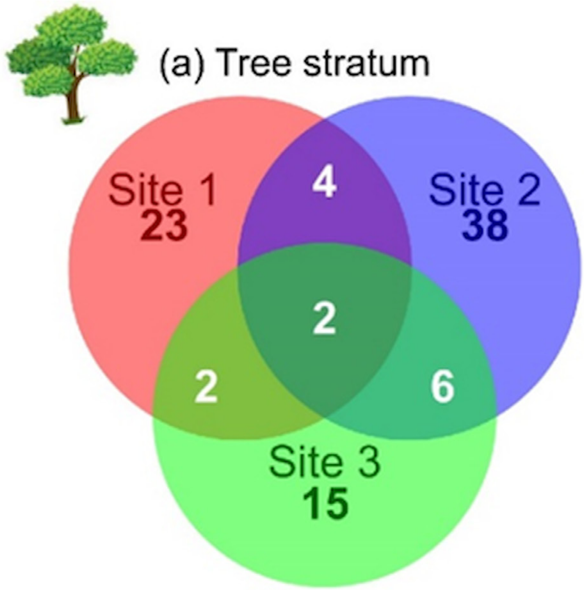

Fig. 3. Venn diagram illustrating the exclusive and shared species among three studied sites from tree (a) and sapling stratum (b) of riparian forests at the upper River Doce watershed, Minas Gerais state, southeastern Brazil. Designations: site 1 – Rio Casca municipality, site 2 – Sem-Peixe municipality, site 3 – Santa Cruz do Escalvado municipality.

Table 1. Soil parameters for the three study sites (N = 15 plots per site) in riparian forests from the upper River Doce watershed, Minas Gerais state, southeastern Brazil

Site	Site 1 M ± SE	Site 2 M ± SE	Site 3 M ± SE
pH (H_2O)	5.20 ± 0.15	4.16 ± 0.09	5.42 ± 0.11
P (mg × dm^{-3})	3.66 ± 0.66	3.67 ± 0.42	2.56 ± 0.51
K (mg × dm^{-3})	31.00 ± 2.76	77.13 ± 6.73	86.87 ± 6.58
Ca (cmolc × dm^{-3})	1.58 ± 0.14	1.32 ± 0.25	4.03 ± 0.62
Mg (cmolc × dm^{-3})	0.60 ± 0.05	0.68 ± 0.10	2.32 ± 0.23
Al (cmolc × dm^{-3})	0.11 ± 0.04	0.87 ± 0.12	0.03 ± 0.02
H+Al (cmolc × dm^{-3})	2.51 ± 0.33	6.80 ± 0.27	3.41 ± 0.20
Base saturation (%)	49.88 ± 4.35	23.51 ± 3.13	63.25 ± 3.00
Al saturation (%)	6.12 ± 2.37	33.21 ± 4.89	0.61 ± 0.52
S (mg × dm^{-3})	7.99 ± 1.67	19.85 ± 1.49	5.05 ± 1.48
Cu (mg × dm^{-3})	1.68 ± 0.08	2.00 ± 0.09	2.15 ± 0.18
Mn (mg × dm^{-3})	60.78 ± 4.46	78.91 ± 13.25	77.85 ± 6.25
Fe (mg × dm^{-3})	70.81 ± 14.39	71.21 ± 7.48	83.91 ± 17.35
Zn (mg × dm^{-3})	2.16 ± 0.14	1.86 ± 0.18	3.54 ± 0.66
Organic C (%)	0.87 ± 0.16	2.15 ± 0.14	1.83 ± 0.11
Coarse sand (%)	47.41 ± 4.02	46.05 ± 2.32	19.27 ± 1.88
Fine sand (%)	28.73 ± 5.50	14.55 ± 0.78	15.63 ± 1.37
Silt (%)	7.09 ± 0.86	6.57 ± 0.84	23.67 ± 0.92
Clay (%)	16.75 ± 2.38	32.83 ± 1.46	41.45 ± 1.95

Note: M – mean value, SE – standard error. Designations: site 1 – Rio Casca municipality, site 2 – Sem-Peixe municipality, site 3 – Santa Cruz do Escalvado municipality.

The co-inertia analysis (COIA) indicated a clear edaphic-floristic gradient in both tree and sapling strata. The overall association between species from the tree stratum and edaphic parameters was highly significant (RV = 0.515; $p < 0.001$) according to the COIA (Monte Carlo with 10 000 permutations). We found a connection of 51.5% between the edaphic and floristic matrices of the tree stratum. The percentage of covariance explained by COIA axis 1 was 67.0%, while axis 2 explained 19.3% of the covariance. Thus, we further explored only the COIA axis 1. The positive side of the COIA axis 1 showed plots with less acidic and nutritionally richer soils with a higher concentration of Ca, Mg, Zn, and silt (Fig. 4a). The species with higher association with the positive side of this axis were *Guarea macrophylla*, *Cecropia pachystachya* Trécul (Urticaceae), *Trichilia pallens* C.DC. (Meliaceae), and *Platymiscium floribundum* Vogel (Fabaceae) (Fig. 4b). On the other hand, the negative side of COIA axis 1 showed plots with more acidic and nutritionally-poor soils with a relatively higher concentration of S, Al, H+Al, and coarse sand (Fig. 4a). The species with higher association with the negative side of this axis were *Trichilia pallida* Sw. (Meliaceae), *Guapira hirsuta* (Choisy) Lundell (Nyctaginaceae), *Sloanea guianensis*, *Actinostemon verticillatus* Baill. (Euphorbiaceae), and *Anadenanthera colubrina* (Fig. 4b).

The overall association between species and edaphic parameters in the sapling stratum was also highly significant (RV = 0.465; $p < 0.001$) according to the COIA (Monte Carlo with 10 000 permutations). We found a connection of 46.5% between the edaphic and floristic matrices of the sapling stratum. The percentage of covariance explained by COIA axis 1 was 68.0%, while axis 2 explained 17.2% of the covariance. Thus, we further explored only the COIA axis 1 for the sapling stratum. The positive side of the sapling-based COIA axis 1 showed plots with less acidic and nutritionally richer soils with a higher Ca, Mg, Zn, and silt concentration (Fig. 5a). The species of the sapling stratum with higher association with the positive side of this axis were *Piper arboreum*, *Astronium graveolens*, *Siparuna guianensis*, and *Miconia* sp. (Melastomataceae) (Fig. 5b). The negative side of sapling-based COIA axis 1 showed plots with more acidic and nutritionally poorer soils with relatively higher Al saturation and higher concentration of Al, S, coarse sand, and H+Al (Fig 5a). The species of the sapling stratum with higher association with the negative side of this axis were *Thyrsodium spruceanum* Benth. (Anacardiaceae), *Amaioua intermedia* Mart. (Rubiaceae), *Guapira hirsuta*, undetermined sp.1, *Trichilia hirta* L. (Meliaceae), and *Myrcia retorta* Cambess. (Myrtaceae) (Fig. 5b).

Discussion

We found differences among the study sites in species composition of the tree stratum and of the sapling stratum. Edaphic parameters explained a great extent of the studied riparian forests assemblages. Other studies also highlight the key role of edaphic factors as a driver of vegetation composition and structure in riparian forests (e.g. Veloso et al., 2014; Fagundes et al., 2019; Figueiredo et al., 2022; Gonçalves et al., 2022), in other types of tropical forests (e.g. Peña-Claros et al., 2012; Ávila et al., 2016; Coelho et al., 2018) and other vegetation types (Le Stradic et al., 2015).

We found the families Fabaceae, Meliaceae, Sapindaceae, Bignoniaceae, Salicaceae, Moraceae, and Rutaceae as the most representative in terms of the number of species and phytosociological importance, confirming the patterns already reported in other areas of tropical riparian forests (e.g. Rodrigues & Nave, 2000). Fabaceae and Meliaceae were the two families with the highest number of species in both tree and sapling stratum. The Fabaceae family is widely distributed in Brazilian biomes, particularly in neotropical forests (Gei et al., 2018).

Regarding the dispersion syndrome, Barbosa et al. (2017) cited *Guarea macrophylla*, *Guapira hirsuta*, *Erythroxylum pelleterianum*, *Sorocea bonplandii*, *Sloanea guianensis*, *Trichilia pallida*, *Trichilia pallens*, and *Trichilia hirta* as zoocoric species indicated for restoration in the state of São Paulo. These species were also recorded in the present study, with *Guarea macrophylla* being the species that exhibits the highest IV in the tree stratum and *Erythroxylum pelleterianum* the species with the highest IV in the sapling stratum. These data corroborate the information available in the literature that there is a predominance of zoochory in tropical forests (e.g. Suganuma et al., 2013). The presence of frugivorous animals influences the floristic composition, ensuring the maintenance of the species in late successional stages, directly affect the structure and dynamics of the community (Beaudrot et al., 2013).

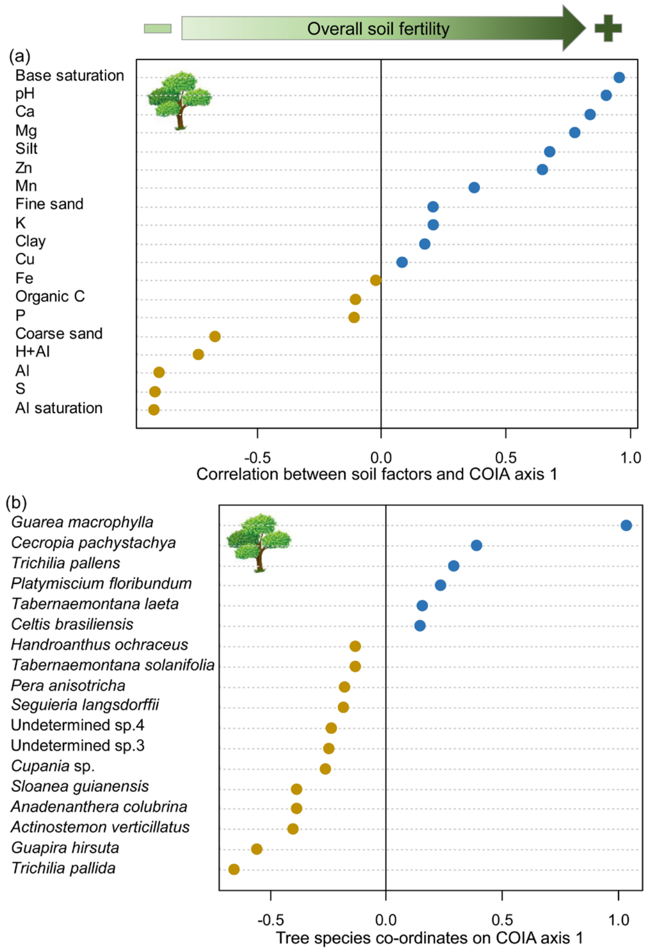

Fig. 4. Co-structure between edaphic parameters and plant species of the tree stratum sampled at Rio Casca, Sem-Peixe, and Santa Cruz do Escalvado municipalities, in riparian forests from the upper River Doce watershed, Minas Gerais state, southeastern Brazil. Designations: a – Pearson's correlation between edaphic factors and plot co-ordinates on co-inertia analysis (COIA) axis 1; b – co-ordinates of plant species from the tree stratum with the highest associations with positive and negative side of COIA axis 1. The green arrow on the top indicates the overall direction of the soil fertility gradient. Orange and blue circles represent, respectively, negative and positive values of correlation (a) or co-ordinates (b) on COIA axis 1.

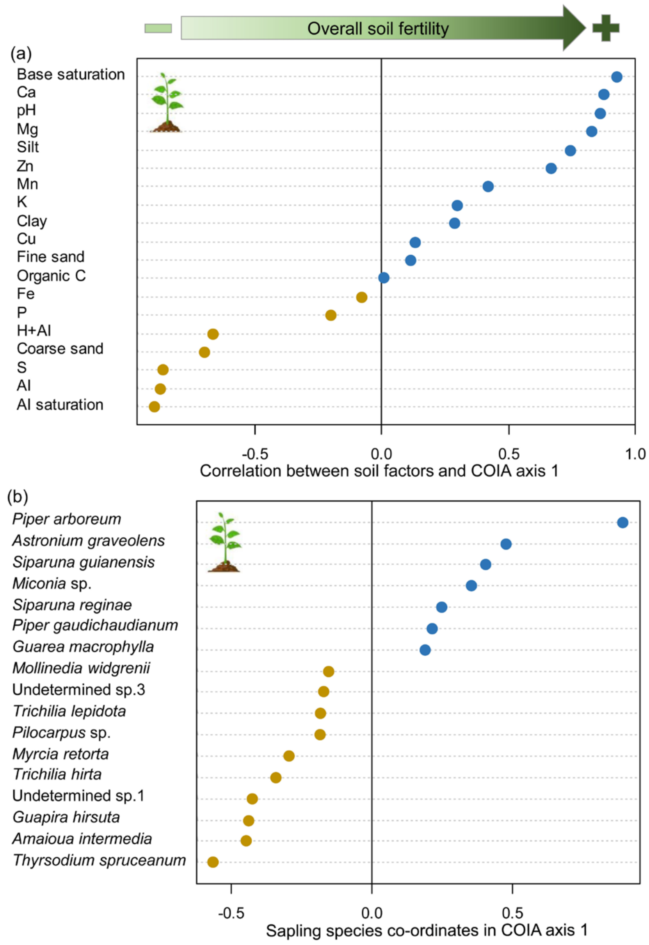

Fig. 5. Co-structure between edaphic parameters and plant species of the sapling stratum studied at Rio Casca, Sem-Peixe, and Santa Cruz do Escalvado municipalities in riparian forests from the upper River Doce watershed, Minas Gerais state, southeastern Brazil. Designations: a – Pearson's correlation between edaphic factors and plot co-ordinates on co-inertia analysis (COIA) axis 1; b – co-ordinates of species of the sapling stratum with the highest associations with positive and negative side of COIA axis 1. The green arrow on the top indicates the overall direction of the soil fertility gradient. Orange and blue circles represent, respectively, negative and positive values of correlation (a) or co-ordinates (b) on COIA axis 1.

The study sites showed various edaphic characteristics, with sandy to clayey soils that favour the establishment of plant species adapted to each microenvironment. Edaphic properties, such as nutrient content, directly influence the composition and distribution of Atlantic Forest species (Coelho et al., 2018; Fagundes et al., 2019; Figueiredo et al., 2022), as well as ecological succession (Pinho et al., 2017; Teixeira et al., 2020; van der Sande et al., 2023). The species *Guarea macrophylla* and *Platymiscium floribundum* were strongly associated with less acidic and nutrient-rich soils, in agreement with previous studies that showed the same relationship (Kotchetkoff-Henriques et al., 2005; Carvalho, 2014). Similarly, the association of the species *Guapira hirsuta* (both strata) and *Amaioua intermedia* (sapling stratum) with sandy and nutrient-poor environments was observed, corroborating the studies by Rodrigues & Nave (2000). The species *Cecropia pachystachya* and *Astronium graveolens* were related to relatively less acidic and more fertile soils, contrary to what was observed by Carvalho (2006) and Braga et al. (2015), where these species were considered indicators of low fertility soils.

In this study, both *Guarea macrophylla* and *Trichilia pallens* were associated with more fertile and less acidic soils. However, in another study developed in a nearby region (Bom Jesus do Galho municipality, distant approximately 50 km in a straight line), these species were associated with less fertile and more acidic soils (Ramos et al., 2023). This apparent inconsistency in the soil affinity of these species can be explained by the absolute values of the edaphic factors, since the more fertile and less acidic soils of the present study corresponded in absolute values to the less fertile and more acidic soils of the Bom Jesus do Galho region (see Ramos et al., 2023). Nonetheless, problems of this nature can be avoided if the results of the association between species and edaphic factors are used to support programmes with a strictly regional focus. Thus, we argue that it is necessary to conduct studies of this nature in each region of interest, without extrapolating this information indiscriminately.

The reference ecosystems presented here suggest that action plans aimed at recovering the riparian forest and increasing connectivity between the remnants should consider the edaphic conditions and its relationship with the plant community on a regional scale. The extrapolation of observed pattern of taxon-environment relationships in local studies may provide wrong standards for programs of re-vegetation and restoration ecology in tropical riverine forests from other regions.

Conclusions

Our findings confirm that edaphic factors strongly influence the floristic composition of riparian forests in the upper River Doce watershed. This highlights the need for restoration strategies that account for local soil conditions rather than applying generalised approaches. The identified reference ecosystems offer critical guidance for restoring degraded areas, especially those impacted by the Fundão dam disaster. Integrating soil-vegetation relationships into restoration planning will improve ecological recovery and ecosystem resilience.

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Supporting Information

Additional data for the paper of Justino et al. (2024) may be found in the **Supporting Information**.

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ФЛОРИСТИЧЕСКАЯ И ЭДАФИЧЕСКАЯ ИНВЕНТАРИЗАЦИЯ АТЛАНТИЧЕСКИХ ПРИБРЕЖНЫХ ЛЕСОВ: РЕКОМЕНДАЦИИ ДЛЯ ПРОЕКТОВ ВОССТАНОВЛЕНИЯ

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Использование инвентаризаций эталонных экосистем для руководства экологическим восстановлением имеет важное значение для мониторинга успешности восстановления окружающей среды. Целью данного исследования было проведение флористической и эдафической инвентаризации остатков старовозрастных прибрежных лесов в верхнем течении р. Досе (Риу-Доси) для предоставления субсидий на программы восстановления. Исследование проводилось в муниципалитетах Риу-Каска, Сен-Пейше и Санта-Крус-ду-Эскалваду. Наибольшее число видов включали семейства Fabaceae, Meliaceae, Sapindaceae, Bignoniaceae и Salicaceae. По химическим свойствам почв участки были значительно разнородны. Так, среди прочих факторов, кислотность почвы варьировала от кислых до нейтральных (pH 3.8–6.3) с различным содержанием фосфора (0.0–7.6 мг × дм$^{-3}$) и насыщенностью алюминием (0.0–66.5%). Анализ коинерции показал высокую значимую связь в 51.5% ($p < 0.001$) между флористической и эдафической матрицами в ярусе деревьев и в 46.5% ($p < 0.001$) между флористической и эдафической матрицами в ярусе подроста. Представленные в данной работе эталонные экосистемы предполагают, что планы действий, направленные на восстановление прибрежных лесов, должны учитывать эдафические условия и их связь с растительным сообществом в региональном масштабе, избегая экстраполяции наблюдаемой картины взаимоотношений таксонов и окружающей среды на другие регионы.

Ключевые слова: взаимосвязь почвы и растительности, водораздел Риу-Доси, прорыв плотины Самарко, растительное сообщество, эталонная экосистема