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Performance assessment of a soil and water bioengineering work on the basis of the flora development and its associated ecosystem processes

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ABSTRACT

The Atlantic Forest of Brazil is one of the world's 25 biodiversity hotspots, but floodplains in this region are continuously converted into agricultural or urban areas, and riverine ecosystems are affected by anthropogenic interventions. Soil and water bioengineering techniques are a component of ecological engineering that can provide nature-based solutions as an alternative or as complementary measures to conventional hydraulic or civil engineering approaches. However, there is a lack of post-evaluation of interventions and there are still great difficulties in identifying valid evaluation criteria and measurement variables, especially in countries like Brazil where soil and water bioengineering measures have only been implemented in the last decade. Another limitation to the widespread application of the techniques is the lack of knowledge about their technical performance, their impact on ecological processes and the evolution of the species used. This study aims to investigate the development of species, evaluate the technical performance of the intervention and assess the ecological benefits and processes of one of the first soil and water bioengineering riparian restoration interventions in Brazil, which was carried out in 2010 on the Pardinho river. Parameters on bank stability, development of species used in different construction techniques and its ecological benefits and ecological processes (plant species and soil fauna richness and diversity, ecological group and recruitment species, invasive species, soil organic matter and soil temperature) were collected over a period of ten years. The study proved that soil and water bioengineering works can both stabilise and control erosion, and at the same time initiate ecological processes on degraded riverbanks. The active introduction of native species has promoted vegetation succession, increased the biodiversity of both plants and soil fauna on the site and improved the site conditions. The establishment of native vegetation led to sediment and organic material deposition, which changed the local ecological conditions (e.g., soil properties, light, flow conditions) and thus facilitated rapid establishment of other plants and re-established interactions between plants and soil fauna groups. This study provides a monitoring approach which examines the technical performance of the measures and species used, as well as their impact on the ecological process over time, which is essential for establishing soil and water bioengineering techniques as the standard in the field of river engineering in Brazil. Furthermore, the results obtained will help in planning and designing future works in the field of soil and water bioengineering in Brazil, adding to the knowledge of the techniques and species to be selected, as well as supporting the evaluation of the success of interventions.

1. Introduction

Riparian zones contain an extraordinarily diverse array of plant species and environmental processes. They have unique values relative to the surrounding landscape (García-Martínez et al., 2017) and provide a wide range of key ecosystem functions and services. Riparian zones are known to stabilise soil on riverbanks, control erosion and sedimentation (Moraes et al., 2014), serve as natural barriers which filter pollution (Rieger et al., 2014), provide important habitats for many wildlife species (Viegas et al., 2014), and connect different habitat fragments

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(Fremier et al., 2015).

The Atlantic Forest of Brazil is one of the world's 25 biodiversity hotspots (Myers et al., 2000), but floodplains in this region are continuously converted into agricultural or urban areas, and riverine ecosystems are affected by anthropogenic interventions including structures to control flooding or prevent channel migration and reservoirs for water supply or energy production. Current estimations place the natural vegetation cover between 12.4% of the original extent of this biome (Fundação SOS Mata Atlântica and Instituto Nacional de Pesquisas Espaciais (INPE), 2020). Its remaining area is highly fragmented and 83.4% of its sustained patches are <50 ha (Rodrigues et al., 2009). Additionally, the Atlantic Forest biome is most vulnerable to pressures related to climate change (Bellard et al., 2014).

In this context, there is a great demand for river engineering approaches which not only take into account technical issues, but also ecological and social values. Soil and water bioengineering techniques are a component of ecological engineering (Rey et al., 2019) which can provide nature-based solutions as an alternative or as complementary measures to conventional hydraulic or civil engineering approaches (Hörbinger, 2021; von der Thannen et al., 2017). These techniques are based on the use of native plants or parts of plants along with inert local material, and can provide both low-cost alternatives for hydraulic engineering and tools for ecosystem restoration in Latin America (Bisso et al., 2016; Petrone and Preti, 2010; Sousa et al., 2021). The active introduction of locally adapted species can improve growing conditions for other native plants to colonize riparian areas and initiate ecological succession. Furthermore, these techniques can improve ecological conditions for riparian biodiversity on degraded riverbanks (Janssen et al., 2019; Rey et al., 2019).

An evaluation of the species and ecosystem processes used is the basis for identifying and replicating the most successful approaches and analyses of the causes of failure (Giupponi et al., 2017; González et al., 2015; Li and Eddleman, 2002; Morandi et al., 2014). However, the development of the measures over time is still an issue which is poorly addressed by the scientific community (Giupponi et al., 2019; Mickovski and Thomson, 2017; Nunes et al., 2016; Rubin et al., 2017). According to Zhang et al. (2019), there is a lack of post-evaluation of soil and water bioengineering interventions and there are still great difficulties in identifying valid evaluation criteria and measurement variables. This point is particularly relevant in Brazil, where there is still a lack of knowledge about the technical performance, impact on ecological process and development of species used in soil and water bioengineering measures.

Soil and water bioengineering in Brazil has only been implemented in a broader context in the last decade. The first projects were performed for slope and riverbank stabilisation, erosion control, protection of linear infrastructure elements and environmental restoration (Holanda et al., 2008; Kettenhuber et al., 2017a; Maffra and Sutili, 2020; Sousa et al., 2017). In addition, several studies have been carried out to investigate the technical properties of native riparian species of the Atlantic forest biome (Dewes et al., 2019; Kettenhuber et al., 2017b; Raddatz, 2019; Sutili et al., 2018; Sutili et al., 2012). However, approaches to monitor the development of soil and water bioengineering interventions are scarce in Brazil. One of the first soil and water bioengineering riverbank restoration works in Brazil was performed at the Pardinho river in 2010. In the present study, both the technical performance and ecological processes related to this project were assessed. The main objectives were as follows: 1) to investigate the development of species used in different construction techniques; 2) to evaluate the technical performance of the intervention; and 3) to assess ecological benefits and ecological processes. It is the first time conducting such an integral assessment of a soil and water bioengineering structure in Brazil taking into account the specific local environmental circumstances.

2. Materials and methods

2.1. Study site

The study site is located on the Pardinho river in the Pardo river watershed in the central region of the state of Rio Grande do Sul, Brazil (Fig. 1). The Pardo river watershed comprises an area of about 3636 km^2, is included in the Deciduous Seasonal Forest of the Atlantic Forest Biome and the land cover is characterized by forest (40.3%), grazing lands (37.1%), agricultural areas (20.6%) and urban areas (1.1%). According to the diagnostic report of the Water Resources Department of the State of Rio Grande do Sul, only 37.3% of the original riparian vegetation remains in the Pardo river watershed area. The riparian vegetation deficit and the intensive land use cause environmental problems such as silting of the drainage beds, landslides and rectification of the natural river course (ECOPLAN, 2005).

As specified by the Brazilian soil classification system, the soil of the region is classified as a Red-Yellow Argisol (EMBRAPA, 2018). The local climate according to the Köppen Climatic Classification is subtropical with humid climatic conditions, hot summers and rainfall during all seasons (Alvares et al., 2013). However, hydrological deficits can occur in months of high temperatures. The seasonal average temperature during the study period ranged between 12.8 °C (winter 2016) and 26.5 °C (summer 2013), and the average seasonal precipitation ranged between 55.3 mm (summer 2019) and 254.9 mm (spring 2015) (BDMET/INMET, 2021).

2.2. Description of the initial situation and objectives of the intervention

The intervention was executed on an actively eroding riverbank section with a length of >80 m located directly below the Dourado reservoir dam. The cause of the erosion processes was the deviation of the river axis towards the left bank due to the construction of a water pipeline. The water flow caused a continuous process of erosion, collapse and landslides. These processes resulted in an embankment with steep angles and low soil resistance characteristics. Additionally, the presence of tall trees along the slope top increased the instability through forming an overhead. The only established species within the embankment was *Pennisetum purpureum* Schum., a highly dominant and invasive alien species in Brazil.

A soil and water bioengineering intervention was installed in order to prevent further erosion processes and mass bank failure. Locally available building materials were used in conceptualizing the construction types. Further goals of the project were to re-establish native riparian species, promote biodiversity, improve soil ecosystem services and push back invasive alien species. The construction was differentiated in the riprap zone and the bank zone. A vegetated riprap was implemented to stabilise the embankment base. It is a solid construction type that can withstand high hydraulic stress. It consists of basalt blocks, *Calliandra brevipes* Benth. seedlings and *Salix humboldtiana* Willd. and *Phyllanthus sellowianus* Müll. Arg. hardwood cuttings. A hedge brush layer with seedlings of four autochthonous shrub species was implemented in the bank zone. In addition, *S. humboldtiana* trees were anchored to the slope in the upper portion. *Enterolobium contortisiliquum* trees were anchored to the slope even further up, but without the expectation of sprouting. As a final measure, the top angle of the slope was smoothed.

However, a flood destroyed parts of the measures in the bank zone shortly after the work was completed in April 2010. Thus, a second vegetative intervention was implemented in October 2010 to ensure the physical integrity of the margin and promote biodiversity. The plant material consisted of 1550 seedlings of 32 species of native shrubs and trees. A detailed description of the implemented structures can be found in Rauch et al. (2014) and Kettenhuber et al. (2017a). No maintenance activities were performed after completing the intervention.

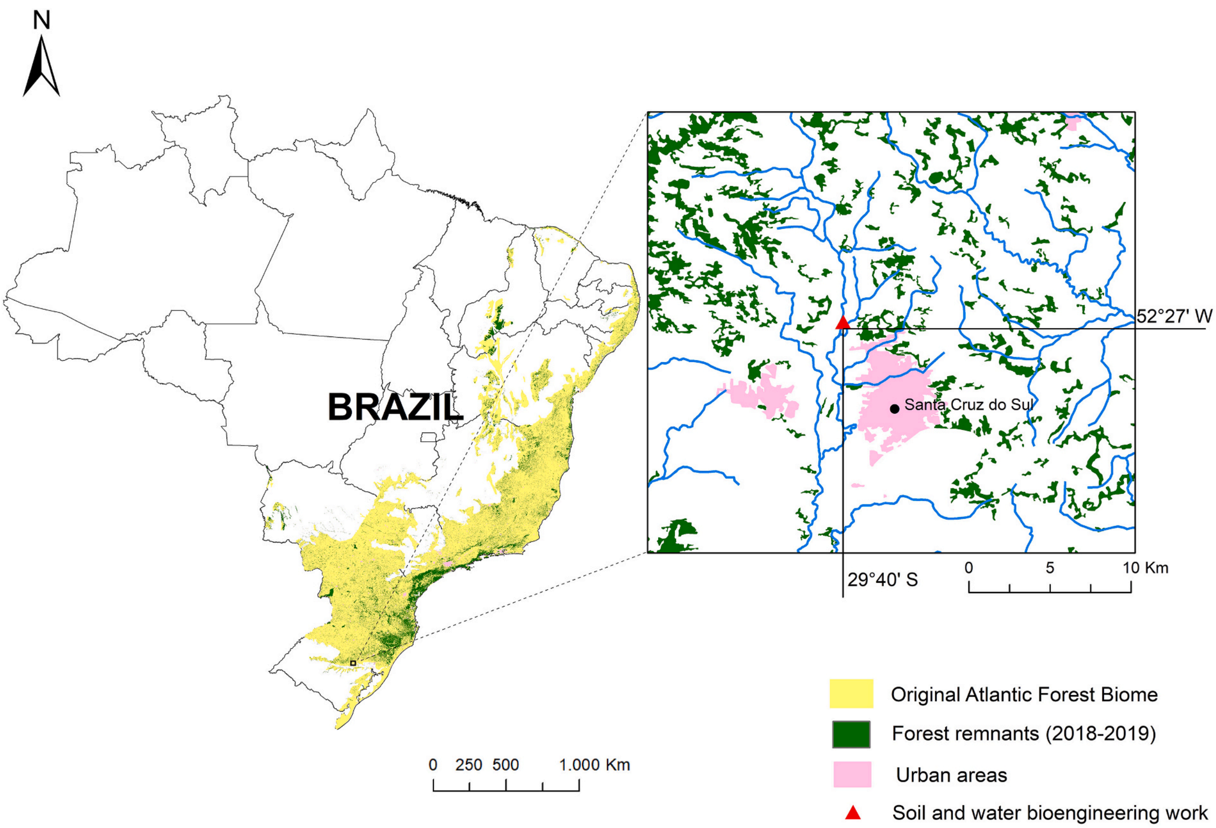

Fig. 1. Location of the study site.

2.3. Integral soil and water bioengineering monitoring approach

The survey parameters have been defined to evaluate both the extent to which objectives were achieved and the temporal development of its related processes. Table 1 shows the collected parameters and the survey time.

Table 1
Collected parameters and the survey time.

Parameters		2010	2013	2017	2020
Bank stability and vegetation development	Tree species [un.]	x	x	x	x
	Density [individual/ area]	x	x	x	x
	Tree height [m]	x	x	x	x
	Tree breast height diameter [cm]	x	x	x	x
	Sedimentation thickness [cm]	–	–	x	x
	Sedimentation area [m^2]	–	–	x	x
Ecological processes	Diversity index [H′]	x	x	x	x
	Ecological group	x	x	x	x
	Recruitment species [un.]	x	x	x	x
	Invasive species coverage rate [%]	x	x	x	x
	Nr. of soil fauna taxons [un.]	–	–	x	–
	Soil fauna abundance [un./m^2]	–	–	x	–
	Soil fauna richness [Nr. of taxa]			x	–
	Soil fauna diversity index [H′]	–	–	x	–
	Soil organic matter [%]	–	–	x	–
	Soil temperature [°C]	–	–	x	–

2.3.1. Riverbank stability

The success of soil and water bioengineering riverbank stabilisation projects depends on the initial establishment and long-term development of vegetative components (Hoag and Fripp, 2002). Particularly in the bank zone where no inert construction materials were used, the development of the plants is decisive for the bank stability. The survival rate and the development of the implemented vegetation were assessed as indicators for the embankment stability. In addition, the sediment deposition thickness was measured at two points (at 4.5 and 8.0 m distance from the mean water level) along five transects. To do so, holes were excavated until reaching the riverbank profile build in 2010. The deposited sediment layer was identified visually, and its thickness and area were measured with a yardstick. The sediment deposition for the total area was estimated by using the average deposition depth and area per transect. These surveys were carried out at 7 and 10 years after stabilisation.

2.3.2. Vegetation development survey

The first vegetation survey was carried out in November 2010, two months after the intervention had been completed. Further vegetation surveys were carried out at 3, 7 and 10 years after stabilisation to examine the development of species and the recruitment of species in the area. The survey of each construction type was conducted along 5 fixed positioned and stripe-shaped parcels of 2 × 15 m extending from the waterline to the top of the slope. Next, the height and the stem diameter of arboreal plants and the height of shrubs were measured. The botanical families and scientific binomen were attributed according to the list of species of Brazilian Flora (Jardim Botânico do Rio de Janeiro - JBRJ, 2020). The vegetation structure was characterized by the number of species and the estimated density for the total area of the intervention. One-way analysis of variance (ANOVA) was performed to compare the development in height and breast height diameter between the evaluations performed. When a significant effect was detected ($p < 0.05$), a post-hoc analysis was performed using Tukey's test. The "ExpDes.pt" package (Ferreira et al., 2014) available in the R software program was used for the analysis (R Core Team, 2022).

2.3.3. Ecological processes survey

The Shannon's Diversity Index (H′) was calculated with the data on the development of vegetation over the years using Eq. (1) (Felfili and Rezende, 2003):

$$(H') = -\sum \text{pi}.log\ \text{pi} \tag{1}$$

In which: pi = ni/N; ni = density of each group, N = $\sum$ of the density of all groups.

The species were classified into four ecological groups: hygrophilous pioneers, pioneers, initial secondary and late secondary. The presence of invasive species was assessed using an adapted Braun-Blanquet scale (Braun-Blanquet, 1964). The coverage rate of invasive plants was estimated by the following classes: 1) single individuals; 2) coverage rate < 5%; 3) coverage rate 5–25%; 4) coverage rate 25–50%; and 5) coverage rate > 50%.

The impact of the intervention on the soil ecosystem was assessed by collecting soil fauna samples, which is an indicator of soil quality (Lavelle et al., 2006; Yin et al., 2019). Soil and litter samples were collected in December 2017 along the embankment in two transects, which extended from the restored riverbank to a reference riverbank located directly downriver. The reference riverbank presents similar characteristics to those of the restored bank before the soil and water bioengineering intervention.

A total of 48 samples (10 × 10 cm in size and 10 cm in depth) were taken in equal distances along the two transects parallel to the riverbank. The first transect is located above the vegetated riprap in an area that is influenced by the river's runoff regime and flood disturbances throughout the year (see Fig. 6). The second transect is located at the top of the riverbank. Soil macrofauna (individuals visible to the unaided eye) was carefully extracted by hand. Based on Southwood (1968), soil *meso*fauna (Acari, Collembola and Protura) was extracted using a Berlese funnel for seven days. The extracted specimens were identified at the level of order and major taxonomic groups using a stereoscopic binocular microscope.

Samples for the chemical characterization of the soil were taken at the same points and depth. The soil temperature was measured using a Digital Infrared Thermometer. The soil meso and macrofauna datasets were based on the mean values per site and per transect. Faunal abundance was calculated as the number of individuals per surface unit (m^2). Faunal diversity was assessed by richness (number of groups) and Shannon's diversity index (H′). One-way analysis of variance (ANOVA) was performed to analyse the effect of restoration in the riverbank. When a significant effect was detected ($p < 0.05$), a post-hoc analysis was performed using the Tukey's test. The "ExpDes.pt" package (Ferreira et al., 2014) available in the R software program was used for the analysis (R Core Team, 2022). In addition to the analysis of variance, a multivariate principal component analysis (PCA) was performed by using the "Factoextra" (Kassambara and Mundt, 2017) and "FactoMineR" (Lê et al., 2008) packages available in the R statistical environment. This analysis was performed to visualize the correlations between the abundance of dominant macro- and mesofauna groups, soil chemical attributes and soil temperature.

3. Results

3.1. Development of vegetation and technical performance of the structures

A total of 69 different species belonging to 57 botanical genera and 37 botanical families were identified in the four vegetation surveys carried out over the years. The results show that the number of individuals and species richness increased in all construction types from 2010 to 2020 (Fig. 2a, b). The total number of individuals and species richness increased from 268 to 702 and 29 to 48, respectively, ten years after stabilisation. An increase in the diversity index was observed in the sections of the hedge brush layers and seedling planting (Fig. 2c). However, there was a noticeable decrease in the diversity index in the hedge brush layer area between the surveys in the seventh and tenth year. The only building type with a significant decrease in the diversity index along all the surveys was the vegetated riprap. The highest diversity 10 years after stabilisation was found in the seedling planting (H′ = 3.16) and the lowest diversity in the vegetated riprap (H′ = 0.33). The distribution of invasive species during the same survey period decreased sharply until it almost ceased in the last inventory (Fig. 2d).

The vegetated riprap was implemented by using *Calliandra brevipes* Benth. seedlings and *Salix humboldtiana* Willd. and *Phyllanthus sellowianus* Müll. Arg. hardwood cuttings. We observed strong dominance of *C. brevipes* in the vegetated riprap 10 years after stabilisation, which increased its population from 75 to 433 individuals during this period (Fig. 3a), and was able to colonize other parts of the stabilisation work (Fig. 3d, f). *P. sellowianus* was only found near the mean water level and showed a slight increase in individuals over time, while *S. humboldtiana* disappeared completely (Fig. 3a).

The species used in the hedge brush layer did not develop as desired in some parts. The implemented vegetation material did not or only sparsely emerged in several spots. Only a few individuals of *Terminalia australis* Cambess. *Schinus molle* L., *Schinus terebinthifolius* Raddi. and none of *Pouteria salicifolia* (Spreng.) Radlk had sprouted in the first years after construction (Fig. 3c). *S. humboldtiana* was prevalent in the first and second surveys in this portion, but then disappeared completely. Spontaneous vegetation mainly consisting of grasses and invasive species had emerged over the whole length of the intervention and was partly dominant in the first years. This area was colonised by other species (Fig. 3d) over time, and invasive species decreased sharply (Fig. 2d).

Changes in plant species composition were also observed in the upper zone of the riverbank, where seedlings of 32 species were initially planted. Many of these species disappeared in the first years (Fig. 3e), but many other species were recruited over the years (Fig. 3f). Only 27 and 17 different species were found in the first two surveys, respectively. However, 40 different species were identified in this part of the slope ten years after stabilisation and among these only 14 species have remained in the area since planting in 2010.

The species which had the highest increase in number of individuals were *Calliandra brevipes*, *Allophylus edulis* (A.St.-Hil., Cambess. & A. Juss.) Radlk., *Schinus terebinthifolius* Raddi, *Myrsine umbellata* Mart., *Prunus myrtifolia* (L.) Urb. and *Ateleia glazioveana* Baill.

The evaluation of the ecological groups revealed variation in the characteristics of the species over the years. Fig. 4 shows that the proportion of the initial secondary species decreased between the first and second assessment and late secondary species completely disappeared. However, the number of species belonging to both strata increased on the riverbank over time. Conversely, the number of hygrophilous and other pioneer species increased in the first years and decreased after the third year.

The plant height and diameter at breast height increased significantly over the years of the survey (Fig. 5). The most significant increase in plant height was observed in the upper zone of the riverbank, where the average height 10 years after construction was about 4.20 m, with some individuals reaching over 8 m. There was a significant difference in plant height for the vegetated riprap and seedling plantation even in the short period between the third and fourth surveys (Fig. 5a). The plant diameter differed significantly between the first and last surveys, showing the strong development of the plants (Fig. 5b).

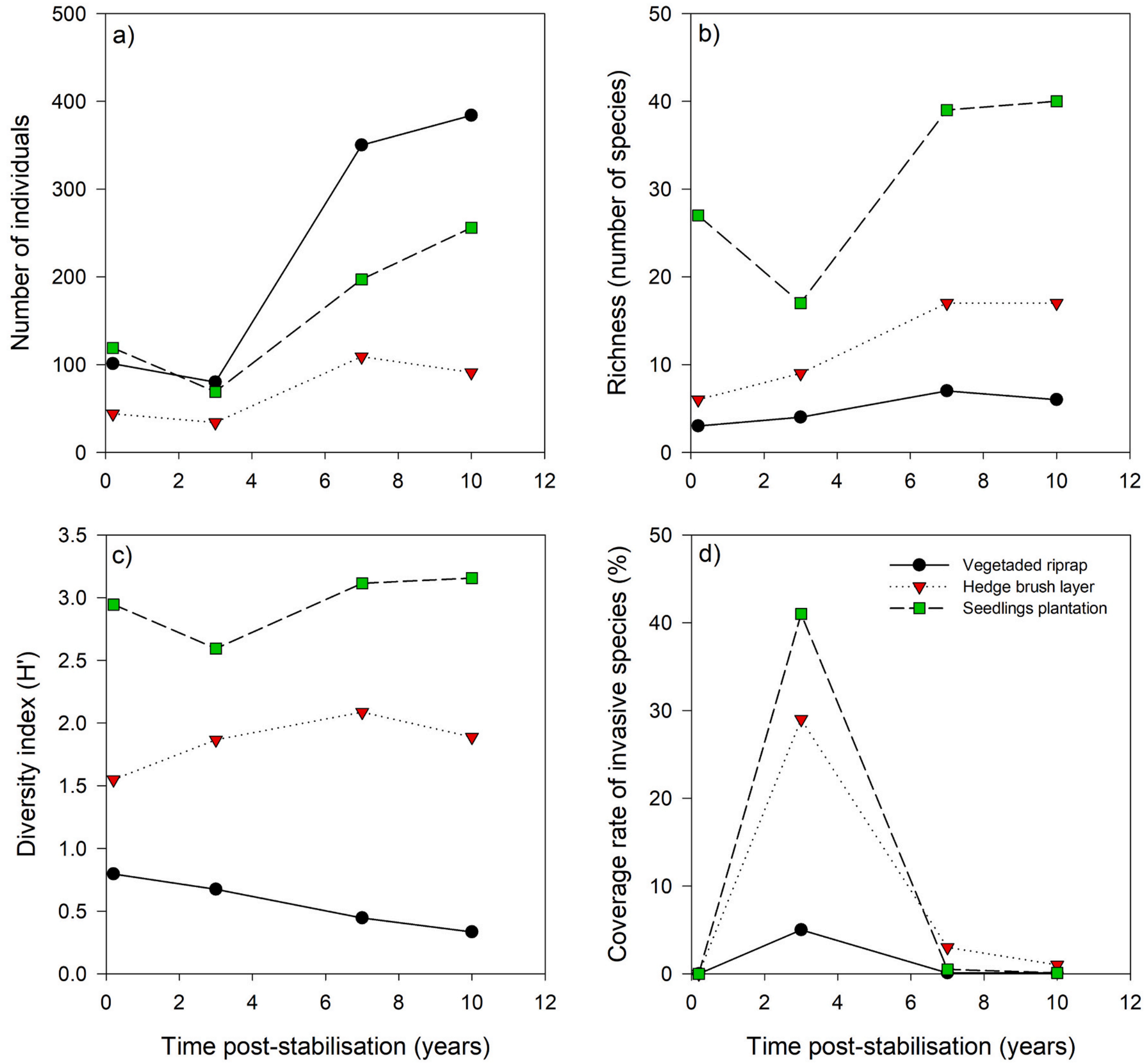

Fig. 2. Variation in (a) number of individuals, (b) species richness, (c) Shannon's Diversity Index (H′) and (d) coverage rate of invasive alien plants in relation to post-stabilisation age and among vegetated riprap, hedge brush layer and seedlings plantation in the soil and water bioengineering work.

3.2. Riverbank stability

The intervention provided effective bank protection over the evaluation period of 3420 days. There were no significant erosion processes observed and the constructed profile was well preserved and stable.

The water level in the evaluation period exceeded the top of the riprap zone (2.3 m) in 241 days (7.0%), and the top of the soil deposit (4.3 m) in 41 days (1.2%). These levels were exceeded on average 26 and 4 days a year, respectively. The highest water level reached over this period was 6.1 m, which corresponds to a discharge of 274.3 m^3/s, a velocity of 1.39 m/s and a particle size of 0.12 m carried by the stream. The discharges and respective water levels are represented in Fig. 6. The hydraulic information is based on the discharge data provided by ANA (2021).

The results of the measurement of sediment deposition are shown in Fig. 6. The estimated deposition volume in the riprap zone was 27.4 m^3 (2017) and 16.6 m^3 (2020), while the values in the bank zone were between 208.9 m^3 (2017) and 180.7 m^3 (2020). The total deposited soil volume was 236.3 m^3 (2017) and 197.3 m^3 (2020). The deposited soil is predominantly sandy with small granulometric particles (silt and clay).

3.3. Soil ecosystem

A total of 3017 individuals were collected, distributed in 21 taxonomic groups of macro- and mesofauna: Acari, Amphipoda, Araneae, Chilopoda, Coleoptera, Collembola, Dermaptera, Diplopoda, Dyptera, Enchytraeidae, Formicidae, Hemyptera, Hymenoptera, Isopoda, Lepidoptera, Oligochaeta, Protura, Pseudoescorpionida, Simphylla, Thysanura and Thysanoptera. The soil and water bioengineering riverbank stabilisation significantly influenced the soil fauna diversity (Fig. 7c). The restored bank zone was the site that presented the highest values for mesofauna abundance and macrofauna richness and diversity (Fig. 7a, b, c). The macro- and *meso*fauna abundance and the mesofauna species richness did not differ significantly between the restored bank zone (RB), riprap zone (RR) or the unrestored bank zone (UB).

Table 2 shows the soil analysis and soil temperature sampled in restored and unrestored areas. It is possible to observe that the greatest variations in the soil parameters among the sites are in the soil organic matter, where the restored bank zone presented the highest value and the unrestored base zone the lowest. Soil temperature differed significantly between restored and unrestored sites, while the average temperature difference was about 6.6 °C and 11.5 °C for the bank zone and the zone closest to the river, respectively.

Principal component analysis (PCA) was performed by extracting the first two components (PC1 and PC2), which together explained 48.1% of the original data variability (Fig. 8). The sampling sites could be efficiently divided with PC1 into the following groups: The first group comprises the restored bank zone sampling sites (green ellipse), the

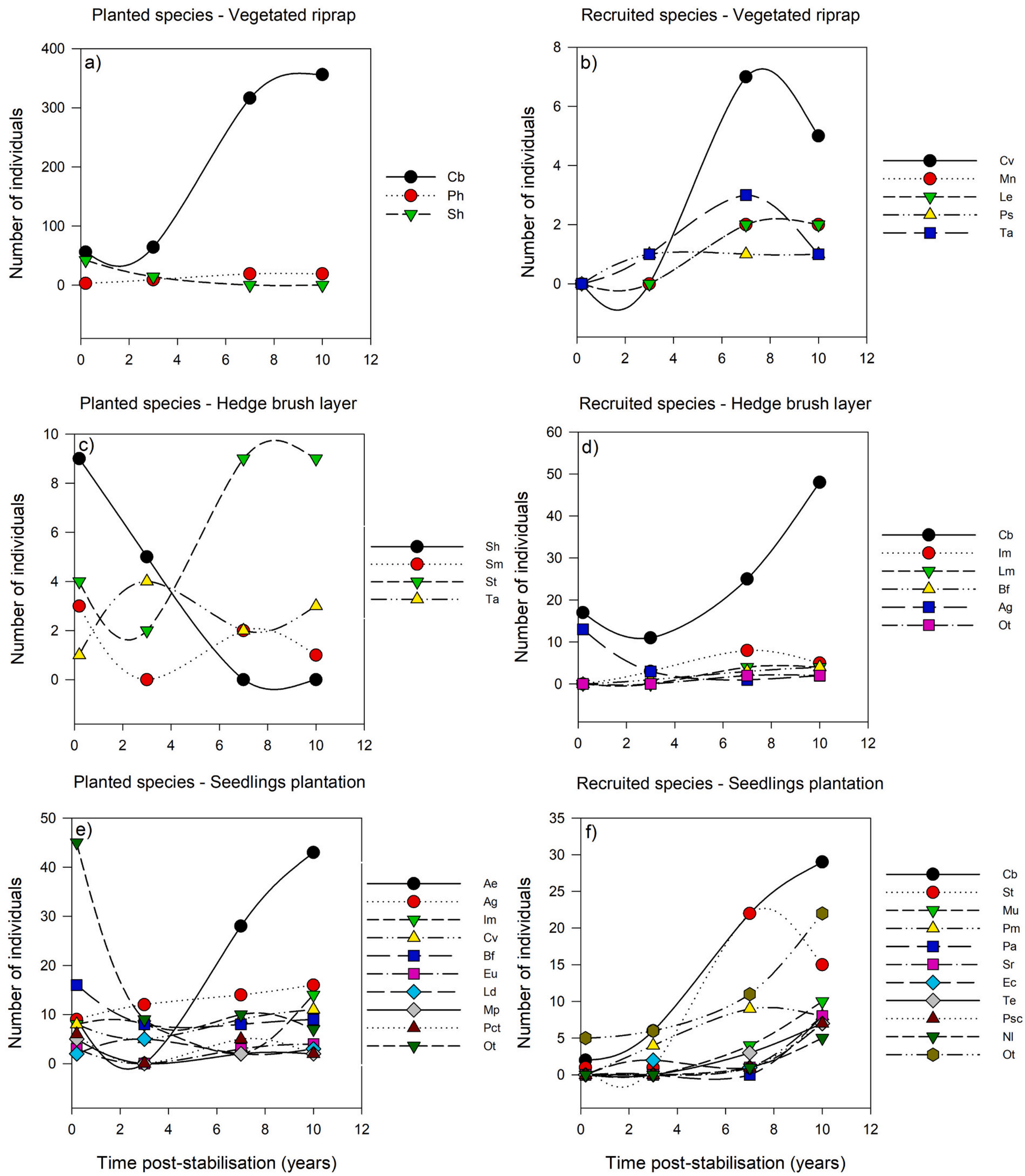

Fig. 3. Variation in number of individuals planted and recruited in vegetated riprap (a, b), hedge brush layer (c, d) and seedlings plantation (e, f) sampled in the soil and water bioengineering work over the years. Cb: *Calliandra brevipes*; Ph: *Phyllanthus sellowianus*; Sh: *Salix humboldtiana*; Sm: *Schinus molle*; St: *Schinus terebinthifolius*; Ta: *Terminalia australis*; Ae: *Allophylus edulis*; Ag: *Ateleia glazioveana*; Im: Inga marginata; Cv: Cupania vernalis; Bf: *Bauhinia forficata*; Eu: *Eugenia uniflora*; Ld: *Luehea divaricata*; Mp: Machaerium paraguariense; Pct: Psidium cattleyanum; Mn: *Morus nigra*; Le: Ludwigia elegans; Ps: Pouteria salicifolia; Lm: Lonchocarpus muehlbergianus; Mu: Myrsine umbellata; Pm: *Prunus myrtifolia*; Pa: *Piper aduncum*; Sr: Siagrus romanzoffiana; Ec: *Enterolobium contortisiliquum*; Te: Trichilia elegans; Psc: Psychotria carthagenensis; Nl: Nectandra lanceolata; Ot: Others.

second group consists of the non-restored bank zone sampling sites (blue ellipse), and the third group consists of the non-restored base zone sites (yellow ellipse). PCA indicated the preferential occurrence of most of macro- and meso fauna groups in restored rather than unrestored areas. In addition, restored areas were associated with higher soil organic matter (SOM), K, Ca and Mg, while unrestored areas were related with higher soil temperatures and pH.

Isopoda, Oligochaeta, Protura, Pseudoescorpionida, Thysanura and Thysanoptera groups were exclusively found at restored areas. >90% of the Collembola and Enchytraeidae groups occurred in the restored area, and the Acari, Aranae, and Coleoptera groups were also primarily found in these areas. All of these groups were correlated with higher SOM, K, Ca and Mg, and negatively correlated with soil temperature. Formicidae and Hemiptera were the only groups where the majority of individuals were found in non-restored areas.

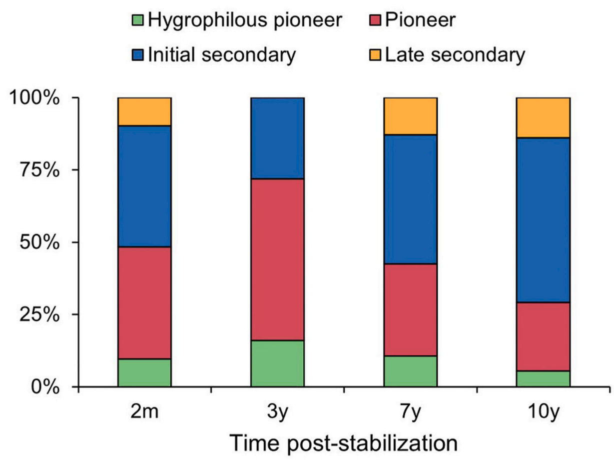

Fig. 4. Distribution of the number of species in ecological groups.

4. Discussion

The monitoring results presented describe the development of a soil and water engineering project over the years and provide comprehensive information about the associated ecosystem functions. Overall, the results clearly confirm that soil and water bioengineering not only plays a role in erosion control and riverbank stabilisation, but can also increase the site biodiversity by promoting vegetation succession following the active introduction of native species and enhancing the site conditions. These results support those of previous studies (Bischetti et al., 2021; Janssen et al., 2019; Schmitt et al., 2018; Tisserant et al., 2020; Zhang et al., 2020), which found that soil and water bioengineering techniques support the habitat quality by accelerating the colonization and establishment of native species and increasing the quality and diversity of wildlife habitats. No further interventions were conducted after installing the structures, which shows that the intervention improved the local site conditions to such an extent that a stable vegetation cover was able to establish through natural succession processes. Improved site conditions enabled spontaneous plant development, as reflected in the increase in species numbers and higher biodiversity index. In particular, the hygrophilous and other pioneer plant species introduced into the study area were able to establish themselves quickly. This led to sediment and organic material deposition, which changed the local ecological conditions (e.g., soil properties, light, flow conditions), and thus facilitated rapid establishment of other plants and life forms.

According to Bischetti et al. (2021), soil and water bioengineering works are able to trigger, activate and accelerate an ecological succession from pioneering species up to a stable climax community, and also provide greater reinforcement than natural revegetation processes.

4.1. Development of species and technical performance of the structures

The results show that the species used and consequently the construction techniques developed very differently. While the highest species richness and diversity index was observed in the seedling plantation zone, the lowest species richness and diversity index were found in the vegetated riprap zone. The diversity index verified in the seedling plantation zone ($H' = 3.16$) is similar to those found in well conserved native forests or in advanced restoration processes (Balestrin et al., 2019; Piaia et al., 2020), demonstrating that this site presented a good structure and high floristic diversity ten years after the stabilisation. In contrast, the diversity index observed in the vegetated riprap was much lower and had decreased over time (Fig. 2c). This zone is constantly influenced by the flow regime (see Fig. 6) and only a few species have the ability to colonize and grow within heavily disturbed areas of the river corridor (Gurnell, 2014). The plant species that colonize riparian and aquatic zones have to cope with an environment where the moisture availability can be highly variable, with frequent flood disturbances and sometimes intense droughts, and with exposed river sediments and little organic material (Gurnell et al., 2012). At the same time, these species can affect the fluvial processes and contribute to stabilise the riverbank. Their aboveground biomass reduces water velocity and retains sediment, while their belowground biomass influences the hydraulic and mechanical properties of the substrate and consequently the moisture regime and reduces susceptibility to erosion (Cavaillé et al., 2015; Corenblit et al., 2009; Gurnell, 2014).

Despite the low diversity in this zone, the installation of the riprap and active introduction of pioneer species, such as *C. brevipes* and *P. sellowianus,* was fundamental for stabilising the whole embankment and enabled the use of softer techniques and a greater diversity of species in the upper zones of the slope.

C. brevipes became dominant in the riprap zone among those species applied, with a very dense growth and production of many shoots. It was able to spread to the upper part of the slope, but did not become dominant there. It provides dense surface coverage, increases hydraulic roughness and enabled sedimentation processes on the riprap. Thus, the species proved to be very appropriate for use in vegetated ripraps and

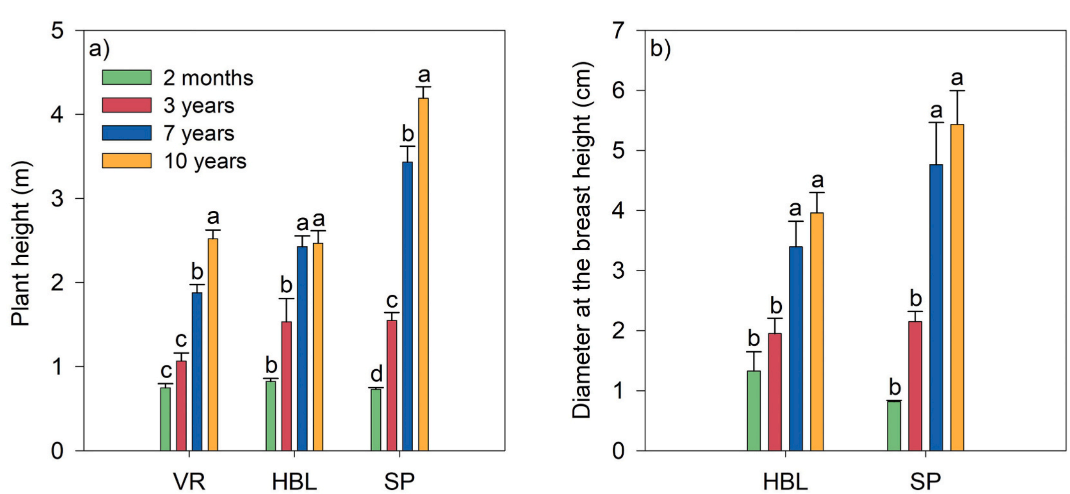

Fig. 5. Plant growth over the years. (a) height of plants in vegetated riprap (VR), hedge brush layer (HBL) and seedlings plantation (SP); (b) diameter of plants in HBL and SP. Note: Values are the mean ± standard error. Different letters indicate significant differences among different time post-stabilisation (Tukey's test $p < 0.05$).

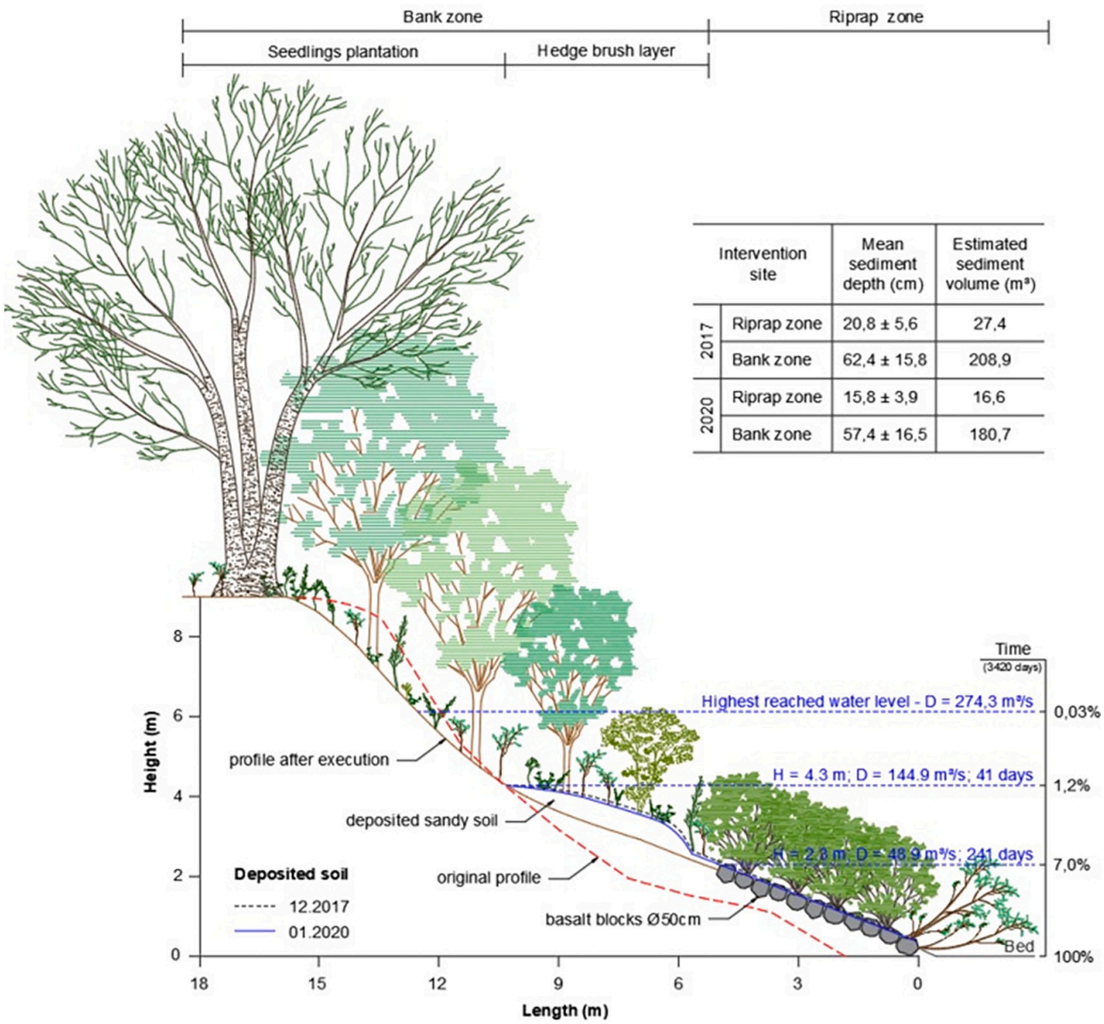

Fig. 6. Slope profiles before and after the soil and water bioengineering intervention, water level and discharge over the evaluation period, sediment deposition along the intervention zones and vegetation development.

has the potential to aesthetically and to some degree ecologically improve this inert construction type. *P. sellowianus* was the only species that succeeded to establish long-term directly at the mean water level. These results are consistent with other studies (Hörbinger, 2013; Rauch and Sutili, 2009) which confirmed the ability of this species to colonize areas directly along watercourses.

A larger number of species were initially applied in the upper zone of the riverbank, contributing to a higher richness and diversity index since the first survey. However, the second survey found a decline in the number of individuals and species, and consequently in the diversity index due to the death of some species, especially those belonging to the most advanced successional groups (Fig. 4). Initial and late secondary species are more demanding of the environmental conditions of the site, such as light and soil fertility and moisture, than pioneer species, developing under intermediate to high shading conditions (Brancalion et al., 2015; Magnago et al., 2015), which may explain the greater mortality of these species in the first years after stabilisation. Conversely, the installed pioneer species (i.e. *A. glazioveana* and *S. terebinthifolius*) most strongly developed in the first years after implementation and significantly declined in the second half of the monitoring period. As expected, as successional advance occurred, the light intensity decreased due to the biomass increment of pioneer species (Fig. 5a, b) (i.e. the canopy became more closed and the available nutrients increased), which in turn allowed the establishment of secondary species, similar to the successional progression of communities undergoing natural restoration (Martins, 2015).

An increase in the number of individuals of the initial secondary species that were applied in the intervention (i.e. *A. edulis* and *Cupania vernalis* Cambess.), as well as the recruitment of new species belonging to this group (i.e. *M. umbellata, P. myrtifolia* and *Nectandra megapotamica* (Spreng.) Mez.) and late secondary species, such as *Psychotria carthagenensis* Jacq. and *Trichilia elegans* A. Juss (Fig. 3e, f) was observed between the second and third assessment. In agreement with Turchetto et al. (2017), the high concentration of initial and late secondary species indicates increased regeneration and promising progress for mature successional stages. In addition, the recruitment of species that were not planted indicates a dispersed flow of seeds coming from surrounding forests. This proves the evolution and advances in the ecological processes in this area which continue to evolve, but have already reached a certain environmental balance.

The species applied in the hedge brush layer did not develop as expected due to their low capacity for vegetative propagation, except for *Salix humboldtiana* which presented good sprouting and was the most prevalent planted species in this zone in the first years after stabilisation. However, it disappeared completely after the second survey (Fig. 3c). The same behaviour was observed in the individuals of this species planted in the vegetated riprap. This is probably due to the faster growth of other pioneer species and canopy closure, as this species no longer found favourable conditions for its development since it is shade-intolerant (Carvalho, 2003; Kettenhuber et al., 2017b).

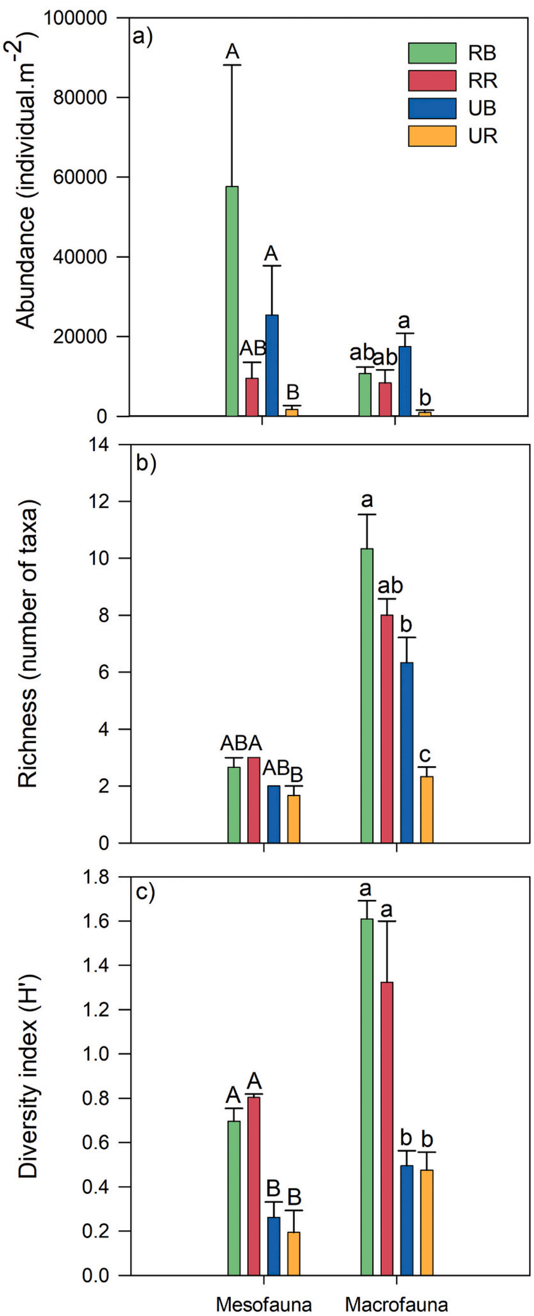

Fig. 7. Soil macrofauna and mesofauna abundance (a), taxonomic richness (b), and diversity (c) in the 0–10 cm soil layer in restored bank zone (RB), restored riprap zone (RR), unrestored bank zone (UB), and unrestored base zone (UR). Note: values are the mean ± standard error. Different capital letters indicate the significant differences among different sites for the mesofauna. Different lowercase letters indicate significant differences among different sites for the macrofauna (Tukey's test $p < 0.05$).

The non-sprouting of most species applied in the hedge brush layer enabled spontaneous species to emerge in this area, mainly the non-native and invasive species *Pennisetum purpureum*. This pioneer species was the only one which established spontaneously on the embankment before installing the intervention. The very strong growth and competitive strength of *Pennisetum purpureum* in the first years restrained the growth of the used plants in some parts of the intervention. However, its population declined sharply with the rapid growth and soil cover provided by some native species applied in the soil and water bioengineering structures until it almost disappeared in the seventh year

Table 2
Soil analysis for each site from samples between 0 and 10 cm in restored bank zone (RB), restored riprap zone (RR), unrestored bank zone (UB), and unrestored base zone (UR).

Site	SOM (%)	pH	Ca (mmolc dm^{-3})	Mg (mmolc dm^{-3})	K (mg dm^{-3})	P (mg dm^{-3})	Average temp. (°C)
RB	4.0	5.9	15.6	5.6	140	16.6	20.2 ± 0.25a
RR	1.9	5.8	13.9	5.0	136	20.3	19.4 ± 0.4a
UB	3.0	5.8	11.3	5.0	128	18.2	26.8 ± 1.3b
UR	0.6	6.2	13.7	5.5	132	13.2	30.9 ± 2.03b

Note: values are the mean ± standard error. Different letters indicate significant differences among different sites (Tukey's test $p < 0.05$).

(Fig. 2d). This fact also shows the successional progress on the embankment.

4.2. Riverbank stability

Strong shrub development in the riprap area and the formation of a riparian forest in the upper part of the embankment could be observed during the survey period. No erosion processes were observed in the soil and water bioengineering intervention, and the embankment could be assessed as stable and safe based on the vegetation development. If there had been bank collapses, landslides or other erosion processes during the observed period, the vegetation would not have been able to develop in this way. The observed sedimentation processes indicate that the vegetation cover had increased hydraulic roughness and therefore reduced flow velocity. The greater volume deposited in the bank zone than in the riprap zone indicates that the flow regime reaches the bank zone with less velocity, having already passed the rough barrier formed by the above-ground part of the hygrophilous plants. This shows that both sedimentary processes in the embankment are dynamic and that the deposited sediment layer constantly remained at a high level. A considerable extension to sediment trapping was provided despite the relatively short length of the restored riverbank (80 m).

4.3. Soil ecosystem

The study showed a positive relationship between a greater diversity of native plant species in the restored areas by soil and water bioengineering techniques and the soil fauna community diversity (Fig. 8). According to de Pereira et al. (2020), a greater diversity of plant species provides greater microhabitat diversification and enhances the structural complexity of the soil resulting from decomposed plant residues. Soil fauna diversity is related to several factors, such as the organic matter concentration and availability in the soil, being present in greater quantities in areas with higher plant diversity (do Machado et al., 2018). Other important factors are soil temperature and humidity, as many groups demand high soil moisture (Baretta et al., 2011; de Vicente et al., 2010), which could explain the presence of some groups only or in higher abundance in the restored areas.

Oligochaeta, Isopoda, Protura, Enchytraeidae and Collembola groups are closely associated with soils which have higher organic matter content and soil moisture (Arenhardt et al., 2021; Baretta et al., 2011; Bianchi et al., 2017). The presence of these groups is important in the soil recovery process. They play an important role in decomposing organic matter and in nutrient cycling; in addition, some of them profoundly modify the soil structure through excavation (Baretta et al., 2011).

The group of predators (such as Aranae and Pseudoscorpionida) represents an important part of the trophic chain. Some species of this

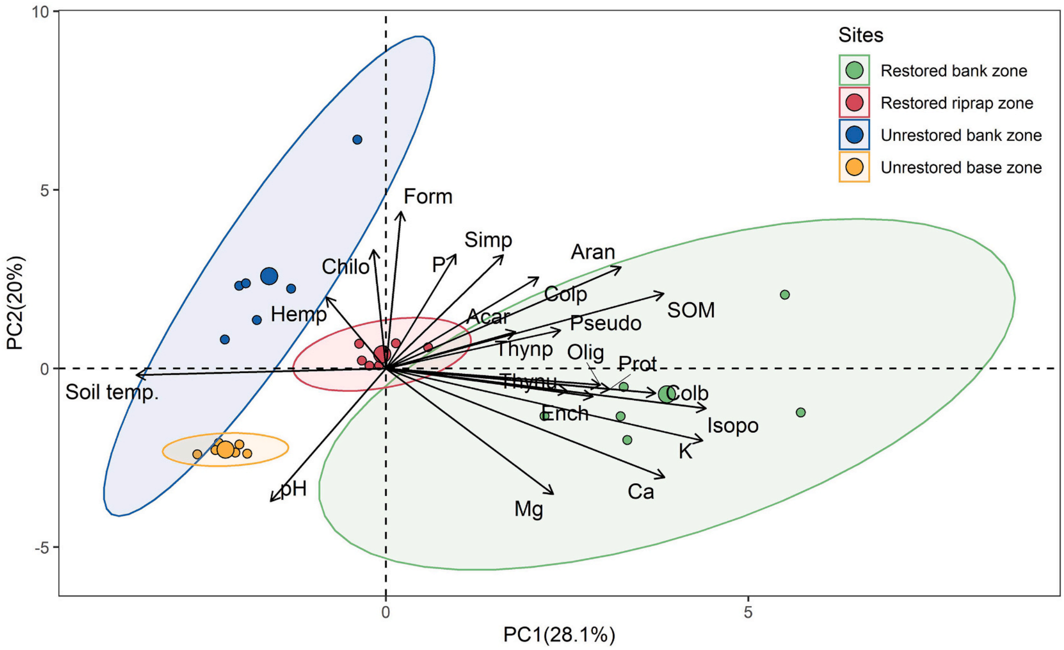

Fig. 8. Principal component analysis of the abundance of major macro and mesophauna groups (Acar: Acari; Aran: Aranae; Colb: Collembola; Colp: Coleoptera; Chilo: Chilopoda; Ench: Enchytraeidae; Form: Formicidae; Hemp: Hemiptera; Isopo: Isopoda; Olig: Oligochaeta; Prot: Protura; Pseudo: Pseudoescorpionida; Simp: Simphylla; Thynu: Thysanura; Thynp: Thysanoptera), soil chemical attributes (SOM: soil organic matter, pH, Ca: calcium, Mg: magnesium, K: potassium, P: phosphorus) and soil temperature of the sampling points across four sites: Restored bank zone (RB), restored riprap zone (RR), unrestored bank zone (UB), and unrestored base zone (UR).

group were found exclusively in the restored areas and only a larger number of individuals occurred here. According to de Vicente et al. (2010), this group is closely related to the system stability, since its absence can lead to a modification in the density of species.

On the other hand, only two groups (Formicidae and Hemiptera) had most of their individuals found in non-restored areas. Ants are one of the largest groups of invertebrates possessing great abundance and diversity all over the world, and some of them can inhabit degraded and high temperature sites (Davidson et al., 2003; Queiroz and Ribas, 2016). Some ant species are generalists and opportunists (de Vicente et al., 2010), which is possibly why they were predominant on the unrestored plots where no natural competitors were able to establish themselves.

Overall, the soil ecosystem survey proved that soil and water bioengineering works were able to improve the habitat quality at the site and re-establish interactions between plants and soil fauna groups.

5. Conclusion

The study emphasizes the necessity for a holistic monitoring approach in soil and water bioengineering works considering both the assessment of technical and ecological aspects. Based on the assessment criteria and metrics used, different ecosystem services and their development over time could be assessed. By considering the technical performance of the interventions, the species used and their impact on the ecological process over time, the method presented provides a basis for a comprehensive monitoring approach. Such assessment frameworks are the basis to establish soil and water bioengineering techniques as a standard in the field of river engineering in Brazil.

The study proved that soil and water bioengineering works can both stabilise and control erosion, and at the same time restore ecological processes on degraded riverbanks. The vegetated riprap proved to be very effective for the immediate protection of the embankment near the water level. Furthermore, undercutting and thus failure of the embankment could be prevented, which allowed continuous vegetation development in the upper part of the embankment. The use of native riparian and pioneer species was fundamental to improve the site conditions in the first years after stabilisation and activated the ecological succession. The construction is providing a suitable living space for plants and enabling spontaneous establishment and development of other plant species. The positive effect of the measure on local site conditions was confirmed by the analysis of the macro- and mesofauna of the soil. The combination of structural measures (i.e. protection of the embankment by the riprap) with the improvement of site conditions by the species used (i.e. improvement of soil and microclimatic conditions) enabled a large variety of species to develop. The results show that a self-sustaining natural system could develop which fulfils the desired technical functions in the long term, and at the same time has added ecological value.

The study also showed that monitoring activities are important in order to set maintenance work, if necessary, as the intervention evolves and the vegetation develops. In this particular case, no maintenance work was required in the 10 years to maintain the function of the structure and achieve this stable condition.

The results provide useful knowledge for planning issues for future design and at the same time many lessons have been learned regarding the suitability of species, the sizing of structures and the potential to initiate ecological processes of different structures. However, there are some issues which could be improved and that should be taken into account in future projects.

The riprap provides a solid basis for the whole soft engineering structure, but creates a very rigid slope line. Alternative soil and water bioengineering techniques could be used here that fulfil the same technical functions but also introduce ecological structures (e.g. deadwood elements). Future soil and water bioengineering interventions should not only consider bank stability, but also aquatic habitat conditions. It will be necessary to enlarge the scale level in the longitudinal and transversal directions in future river restoration projects to link the terrestrial and the aquatic system.

CRediT authorship contribution statement

Paula Letícia Wolff Kettenhuber: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Rita dos Santos Sousa:** Conceptualization, Methodology, Investigation, Writing – original draft. **Júnior Joel Dewes:** Conceptualization, Methodology, Investigation, Writing – original draft. **Hans Peter Rauch:** Conceptualization, Methodology, Supervision. **Fabrício Jaques Sutili:** Conceptualization, Methodology, Supervision, Project administration. **Stephan Hörbinger:** Conceptualization, Methodology, Investigation, Writing – original draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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